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Ultra-High Voltage Line UAV Inspection Technology

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Abstract: Ultra-high voltage (UHV) transmission lines, as the backbone of national energy transmission, are crucial for their safe and stable operation. However, traditional manual inspection methods suffer from low efficiency, high labor intensity, significant safety risks, and limitations due to terrain and climate conditions, as well as observation blind spots, making them inadequate for the intelligent operation and maintenance (O&M) needs of modern power grids. The rapid advancement of drone technology has brought revolutionary breakthroughs in UHV line inspections. This article aims to systematically explore the application of drone inspection technology in UHV scenarios, focusing on its technical principles, system composition, core advantages, and challenges. The research covers key technologies such as drone platform selection, the functions and applications of critical mission payloads, high-precision positioning and navigation, autonomous obstacle avoidance, strong electromagnetic environment adaptability, multi-sensor fusion, and intelligent defect recognition based on deep learning. Through case studies, it demonstrates that drone technology significantly enhances inspection efficiency and coverage, reduces operational risks and costs, and achieves precise and intelligent detection. Although there are still challenges in endurance, adaptability to complex environments, data processing efficiency, and standardization, drone inspection technology represents the inevitable direction for the intelligent O&M of UHV lines. Its deep integration with cutting-edge technologies like artificial intelligence, digital twins, and cluster collaboration will usher in a new era of transmission line O&M.

Keywords: ultra-high voltage transmission line; UAV inspection; power system security; intelligent operation and maintenance; fault detection; multi-sensor fusion

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1. Introduction

Ultra-high voltage transmission lines, the backbone of the national power grid, are responsible for the core task of transmitting large volumes of electricity over long distances across regions. Their safe and stable operation is crucial to the nation's economic lifeline and energy security. As the power grid expands and its operational years increase, potential failure risks due to aging equipment, environmental erosion, and external damage have become increasingly prominent. Traditional manual line inspections, which rely on foot patrols or tools like telescopes and tower climbing, face numerous challenges: low inspection efficiency, difficulty in covering extensive line corridors, especially in mountainous, forested, and swampy areas with complex terrain and poor transportation; inspectors must work closely with or climb high-voltage facilities, facing high safety risks such as electric shock, falls, and wildlife attacks; inspection quality can be affected by the inspectors' skills, physical condition, and subjective judgment, leading to blind spots and missed inspections; inspections during adverse weather or special periods are limited, making it difficult to respond promptly to sudden failures. These issues severely limit the maintenance and operational capabilities and safety assurance of ultra-high voltage lines [1-5].

In recent years, the rapid advancement of drone technology, particularly in platform stability, mission payload diversity, intelligent flight control, and automated data processing, has opened up new technical avenues for addressing traditional patrol challenges. Drones, with their flexibility, mobility, terrain adaptability, close-range observation capabilities, advanced sensor integration, and significantly reduced human operational risks, have rapidly gained widespread application and in-depth exploration in power line inspection. Internationally, developed countries such as Europe, America, and Japan have accumulated substantial experience in applying drone technology for power line inspections, setting standards, and conducting intelligent analysis. Supported by national energy policies and actively promoted by power grid companies, China's drone power line inspection technology has seen rapid development, with its application scale continuously expanding and the technical system becoming increasingly sophisticated. It has become a crucial component of intelligent operation and maintenance of transmission lines. Current research focuses on enhancing drones' stability and interference resistance in ultra-high voltage environments, extending their endurance, developing high-precision autonomous obstacle avoidance and route planning algorithms, achieving real-time transmission of massive inspection data, and implementing AI-based automatic defect recognition. In the future, drone patrol technology will evolve towards higher levels of intelligence, cluster collaboration, deeper integration with digital grids and digital twin technologies, expanded special operation capabilities, and the promotion of standardization and regulation [6-8].

This study focuses on the intelligent UAV inspection technology for ultra-high voltage transmission lines, aiming to systematically explain its technical framework, application effectiveness, and future development. The main content includes: a detailed analysis of the structural characteristics, typical defects, and technical requirements for UAV inspections in ultra-high voltage lines; a thorough explanation of the core components and functional implementation of the UAV inspection system; a focused discussion on key technologies suitable for ultra-high voltage environments, such as high-precision positioning and navigation, protection against strong electromagnetic interference, autonomous flight obstacle avoidance, multi-sensor collaborative detection, and deep learning defect recognition; an objective evaluation of the significant advantages and current challenges of UAV inspections, along with proposed strategies to address these challenges; through the analysis of typical application cases, the practical value of the technology is demonstrated; finally, the study looks ahead to the future trends and comprehensive benefits of the technology. The research methods primarily involve a combination of literature reviews, technical comparisons, case studies, and field application evaluations. The structure of the thesis follows the logical thread of research background and current status, technical principles and systems, key technologies, application analysis, and benefit prospects [9-12].

2. Technical Principle and System Composition of UAV Line Inspection for Ultra-High Voltage Lines

Ultra-high voltage transmission lines are characterized by their complex structure and numerous components, including towers, conductors, insulator strings, hardware, and ancillary facilities. These lines operate in an exposed environment, enduring high voltages, large currents, mechanical stresses, and environmental factors such as wind, frost, rain, snow, lightning, pollution, and ice accumulation, which can easily lead to various defects and faults. Common defects include: conductor breaks or damage due to lightning strikes, external forces, or material fatigue; insulators that flashover, have low or zero values, or self-explosion due to degradation, pollution, lightning strikes, or manufacturing defects; hardware overheating due to poor contact, corrosion, or loosening; abnormal discharges from conductors, ground wires, and hardware caused by corona or electric arcs; insufficient safety distances due to excessive growth of trees and bamboo within the line corridor; and issues like ice overload, foundation settlement, and theft of tower materials. These defects place stringent demands on inspection technology: ensuring high safety during inspections to prevent risks to line operation and personnel equipment; accurately identifying and locating subtle or potential defects; having a wide coverage area and high inspection efficiency to handle complex terrains and adverse weather conditions; and obtaining comprehensive multi-dimensional data to support condition assessment.

The drone patrol technology is a comprehensive system designed to meet these needs. Its core system consists of four main components: the drone platform serves as the aerial carrier. To meet the long-distance and detailed inspection requirements of ultra-high voltage lines, multi-rotor drones and vertical take-off and landing fixed-wing drones are primarily used. Key selection criteria include flight duration, payload capacity, wind resistance stability, positioning accuracy, electromagnetic compatibility design, and environmental protection rating. The mission payload acts as the core "sensory" for monitoring line conditions. A high-definition zoom visible light camera captures high-definition images of the equipment's appearance, identifying issues such as missing or loose hardware, damaged insulators, conductor and ground wire damage, and foreign object hanging. An infrared thermal imager detects temperature distribution on the equipment's surface, accurately locating abnormal hot spots caused by increased contact resistance at conductor connection points, line clamps, and insulator steel caps, diagnosing potential faults. A UV imager keenly captures weak UV signals produced by corona discharge and arc, detecting early-stage discharge from insulator contamination flashover, corona on hardware, and conductor damage points. A LiDAR emits laser pulses and receives reflected signals, creating a high-precision 3D point cloud model of the line corridor and surrounding environment, enabling automatic and precise measurement of tree obstruction distances, calculation of conductor sag, analysis of crossing and spanning, and topographic mapping. Some special applications also explore the use of multispectral/high-spectral payloads. A high-performance stabilized gimbal ensures that various payloads maintain stable pointing towards the target during flight vibrations. The Ground Control Station (GCS) serves as the command center for operations, equipped with flight control software. It is responsible for task route planning, real-time monitoring of UAV status, issuing flight commands, payload control, and the real-time transmission and preview of collected data. A stable and reliable data link communication system is essential for remote control and data transmission, with its interference resistance and communication range being critical. The data processing and analysis platform acts as the value extraction center, handling the storage, management, and preprocessing of massive inspection raw data. At its core, it uses deep learning-based artificial intelligence algorithms to automate data analysis, enabling intelligent recognition and classification of defects such as insulator self-explosion or flashover marks, pin missing detection, conductor breakage or foreign object identification, hot spot location and grading, and corona discharge point marking. The platform ultimately generates standardized inspection reports and integrates with the power grid GIS geographic information system and PMS production management system, achieving closed-loop management and condition assessment of defects.

The typical drone patrol operation process is a standardized closed loop: in the preparatory stage, tasks include airspace application and approval, meteorological condition assessment, detailed route planning based on the line ledger and inspection targets, and comprehensive checks of the drone system and backup equipment. During the on-site flight operation phase, operators direct drones to perform autonomous patrols according to the planned routes, while monitoring the flight status and transmitting images in real-time from the ground station. For key suspicious areas or complex components, manual mode can be switched for close-up detailed inspections. In case of emergencies, emergency plans must be activated. Throughout the flight, various mission payloads continuously collect data, which is either transmitted back in real-time via the data link or stored in onboard devices for download after the flight. The core value lies in the subsequent data processing and analysis, where raw data is imported into a professional platform for data organization and preprocessing, and AI algorithms are used for automated defect identification and manual verification. A detailed inspection report, including the location, type, level, and image evidence of defects, is generated and pushed to the operation and maintenance management system to guide the formulation of subsequent maintenance plans and the completion of defect elimination in a closed loop, thus completing a full cycle of inspection tasks.

3. In-Depth Analysis of Key Technologies of UAV Line Survey

The efficient, accurate and safe implementation of UAV inspection on ultra-high voltage lines depends on the breakthrough and integrated application of a series of core key technologies, which together constitute the technical pillar supporting intelligent line inspection.

High-precision positioning and navigation technology are the cornerstone for drones to safely fly through complex power grid corridors. Real-time dynamic differential (RTK) and post-processing dynamic differential (PPK) technologies enhance drone positioning accuracy from meters to centimeters by receiving base station or satellite-based augmentation signals. This is crucial for maintaining precise and safe distances in ultra-high voltage environments with dense conductors and numerous hardware components. However, the strong electromagnetic fields generated by ultra-high voltage lines can significantly interfere with satellite signals and internal sensors of drones, leading to positioning drift or failure. To address this, a combined navigation strategy that integrates multi-source information is required, including high-precision inertial measurement units (IMUs), visual odometry (VOs), and even LiDAR point cloud matching. This strategy ensures continuous and reliable navigation when satellite signals are interfered with or temporarily lost, and minimizes the impact of electromagnetic interference through rigorous electromagnetic shielding design, sensor redundancy, and adaptive filtering algorithms.

Autonomous flight and intelligent obstacle avoidance technology are the core drivers for achieving efficient automated inspections. Based on the three-dimensional model of the line and the global path planning algorithm for inspection targets, the optimal initial route is generated. When encountering dynamic obstacles or static but unmodeled obstacles, drones must rely on real-time perception systems for local dynamic obstacle avoidance. This typically involves integrating visual sensors, millimeter-wave radar, and LiDAR, using SLAM technology to perceive the surrounding environment in real time. In ultra-high voltage environments, the obstacle avoidance strategy must be particularly optimized: the system must accurately identify thin conductors, strings of insulators, and complex tower structures, calculate their three-dimensional spatial positions, and develop targeted avoidance rules to ensure absolute safety in near-electricity environments.

The technology for adapting to a strong electromagnetic environment poses a significant challenge for ensuring the stable operation of drones in ultra-high voltage fields. The powerful power frequency electric and magnetic fields generated during line operation can couple into the drone's flight control circuits, communication links, and magnetic sensors, leading to control signal distortion, communication interruptions, navigation errors, and even loss of control. To address this, a multi-layered strategy is employed: first, in hardware design, conductive composite materials or metal foils are used to shield key electronic compartments from electromagnetic interference, cable layouts are optimized to reduce loop areas, and components with high immunity are selected; second, at the software algorithm level, adaptive filtering algorithms are developed to filter out power frequency interference signals in real time, enhance the error correction capabilities of communication protocols, and seamlessly switch to a heading calculation mode based on gyroscopes and accelerometers when the magnetic compass fails; finally, operational standards are established through electromagnetic field simulations and actual measurements, defining the minimum safe operating distances under different voltage levels and operating conditions, and embedding these standards into the flight control system as no-fly zones. These measures collectively form a defense against strong electromagnetic interference.

Multi-sensor fusion and collaborative detection technology is crucial for enhancing the comprehensiveness and accuracy of condition perception. A single sensor cannot fully capture all potential defects in a line. Sensors such as visible light, infrared, ultraviolet, and LiDAR must be precisely aligned in terms of spatiotemporal reference to ensure that the positions of the same equipment components are accurately matched across different modal data. The fusion strategy involves: using the precise three-dimensional coordinates from LiDAR point clouds as the spatial reference, mapping the two-dimensional images of visible light, infrared, and ultraviolet onto this reference; ensuring consistent data collection times across sensors through time synchronization devices; developing information fusion algorithms, such as identifying abnormal locations on equipment surfaces using visible light image recognition, verifying overheating by calling the corresponding infrared temperature data, or using ultraviolet discharge point information to assist in assessing the contamination status of insulators.

Deep learning-based defect intelligent recognition technology is a powerful tool for overcoming the bottleneck in massive data processing. The core of this technology involves building a high-quality sample library and enhancing data, followed by training high-performance convolutional neural network models. The YOLO model is used for target detection to identify issues such as insulator self-explosion, pin loss, anti-vibration hammer displacement, and conductor foreign objects. An image segmentation model is employed to precisely locate areas of conductor fractures or insulator flashover marks. A classification model is utilized to assess the severity of hot spots or corona discharge intensity. Given the diverse models of power equipment and the scarcity of defect samples, transfer learning and small-sample learning techniques are essential for improving the model's generalization ability and practicality. The model's performance must be rigorously evaluated using metrics like precision, recall, and F1 score, with continuous iterative optimization.

4. Advantages of UAV Line Survey

The application of drone technology in ultra-high voltage line inspection has demonstrated revolutionary comprehensive advantages over traditional manual methods, profoundly transforming the transmission operation and maintenance model. The core advantages are primarily reflected in a significant leap in efficiency and coverage. Drones can navigate through complex terrains, quickly reach target areas, and complete inspections or detailed checks on key poles and towers over tens of kilometers in a single flight, with operational efficiency several to dozens of times higher than manual inspections. This is especially crucial for wide-area transmission networks, where rapid coverage is essential. Secondly, the safety of drone inspections has seen a qualitative improvement. Inspectors no longer need to climb high towers or come into close contact with live equipment, thus eliminating major personal safety risks such as falls from heights, electric shocks, and wild animal attacks. It also reduces potential interference with line operations, significantly enhancing the intrinsic safety level. Thirdly, there has been a breakthrough in detection accuracy and data dimensions. Equipped with high-definition zoom cameras, drones can clearly capture missing pins at the millimeter level or minor damage to the conductor surface; infrared thermal imagers can non-contactally and accurately locate hidden overheating hazards, with temperature measurement accuracy reaching ±2℃ or higher; ultraviolet imaging devices can sensitively detect corona discharge phenomena;

and LiDAR can precisely measure tree obstruction distances and conductor sag, constructing a three-dimensional channel model with centimeter-level precision. These multi-source heterogeneous data provide unprecedented, comprehensive, objective, and quantifiable evidence for equipment condition assessment. Fourthly, the flexibility of operations and environmental adaptability have been enhanced. Drones can operate in areas that are difficult for humans to reach, during adverse weather conditions, and even at night, significantly expanding the time and space for effective inspections. Fifth, promoting the intelligent and digital transformation of operation and maintenance. By integrating massive inspection data with artificial intelligence analysis, drones can automatically identify, classify, and warn of defects, significantly reducing the time spent on manual judgment and minimizing subjective errors. The data can be directly integrated into the power grid's GIS and PMS systems, laying a solid foundation for condition-based predictive maintenance and digital asset management. Sixth, significant overall economic benefits. Although there is an initial investment, in the long run, drones significantly reduce labor costs, vehicle wear and tear, and the cost of planned outages due to inspections. More importantly, they prevent costly fault outages and emergency repairs by identifying defects early, resulting in a high overall return on investment.

5. Application Case Analysis

5.1. Case 1: UAV Infrared Precise Positioning of Overheating Defects of 500kV Tension Line Clamp

During a routine inspection of a critical 500kV ultra-high voltage transmission line, the maintenance team planned to use drone infrared temperature measurement technology to identify potential overheating issues at connection points. For this task, they selected a multi-rotor drone equipped with high-precision infrared thermal imaging and excellent electromagnetic interference resistance. The focus was on the tension towers, which are prone to overheating due to the high mechanical stress on their hardware. The drone flew along a pre-set route, performing multi-angle infrared scans on the target tension clamps from a safe distance of about 15-20 meters from the conductor side. The infrared data was transmitted in real-time to the ground station, clearly showing that the B-phase tension clamp of one tower had a significant temperature anomaly. The thermal image showed that the temperature of the clamp reached 98°C, while the temperatures of the adjacent clamps and conductors were within normal ranges, indicating a significant temperature difference. The AI-assisted analysis system quickly triggered an alarm and marked the abnormal point. Back-end professionals reviewed the visible light high-definition images, ruled out external attachments and other interference factors, and confirmed that the clamp was severely overheated due to increased internal contact resistance, posing a risk of melting. Thanks to the efficiency and precise positioning of the drone's infrared inspection, the maintenance department promptly arranged for live-line work teams to perform emergency repairs, replacing the faulty clamp. This successfully prevented a potential unplanned outage of the 500kV line due to connection point burnout, ensuring grid safety and minimizing direct economic losses and social impact.

5.2. Case 2: Lidar Accurate Ranging to Solve the Crisis of Tree Obstacles

A 220kV line that traverses dense mountain forests has long been threatened by tree obstructions. Traditional manual inspections, which rely on visual estimation and experience to judge tree height and distance, are both imprecise and inefficient. This is particularly problematic in steep areas where access is difficult, leading to significant blind spots and a lack of quantifiable data. To accurately assess channel risks and guide clearance efforts, the operation and maintenance unit has adopted a fixed-wing drone equipped with high-precision LiDAR for scanning tree obstructions along the line corridor. The drone flies along the line corridor, emitting laser pulses from the LiDAR to capture point cloud data of the channel and its surrounding vegetation. The data processing platform filters and classifies the point cloud, accurately reconstructing the three-dimensional positions of the conductors and the spatial distribution of nearby trees. The algorithm automatically calculates the minimum clearance distance between the highest point of each tree and the conductor in three-dimensional space, setting risk level thresholds according to the "Electric Power Safety Work Procedures". The analysis reveals that multiple tree obstruction points have entered the warning or even critical distance range, especially several ultra-high trees located in steep valleys and hard-to-reach areas. The platform automatically generates reports and visual maps containing precise coordinates of the risk points, tree heights, clearance distances, and risk levels. Based on this precise quantitative data, the operation and maintenance department has developed a scientific clearance plan, prioritizing critical points to avoid unnecessary cutting, significantly improving clearance efficiency and cost-effectiveness. This ensures the safety margin after the line is upgraded and operates at higher voltage, effectively preventing the risk of tree flashover tripping.

5.3. Case 3: Practice of UAV Cooperative Inspection of Ultra-High Voltage Lines in Complex Mountainous Areas

The 500kV line segment under the jurisdiction of a regional power grid is located in a remote mountainous area, characterized by steep terrain, deep ravines, and dense vegetation, making transportation extremely challenging. Traditional manual inspections are time-consuming, labor-intensive, and carry high risks, making it difficult to conduct thorough and detailed inspections. To address this challenge, the operation and maintenance team innovatively adopted a "vertical take-off fixed-wing aircraft + multi-rotor UAV" collaborative inspection model. First, the vertical take-off fixed-wing aircraft, equipped with a wide-angle visible light camera, conducts long-duration, large-scale rapid inspections of the channel, quickly identifying obvious issues such as tree obstructions, external damage, and tower base abnormalities, and pinpointing key poles and towers for further inspection. Subsequently, for the selected key poles and towers, multi-rotor UAVs equipped with high-definition zoom cameras and infrared thermal imagers are dispatched to perform detailed inspections. The multi-rotor UAVs, with their excellent hovering stability and maneuverability, can take high-definition photos and perform infrared temperature measurements from multiple angles on critical components such as insulator strings, hardware, conductor joints, and voltage balancing rings within 5-15 meters of the equipment. This collaborative inspection completed in just a few days what previously required weeks of manual inspection of mountainous lines. The results were significant: high-definition images revealed three instances of insulator self-explosion, multiple anti-vibration hammers out of position, and one instance of foreign object hanging on the conductor; infrared temperature measurements detected one instance of slight overheating at a tension clamp; and channel inspections confirmed multiple tree obstruction points that needed monitoring. This significantly increased the inspection coverage and defect detection rate of the difficult section of the line, while minimizing personnel safety risks and fully demonstrating the irreplaceable value of drones in extremely complex terrains (Figure 1).

Figure 1. Workers Carry Out Inspection of Ultra-High Voltage Lines.

6. Conclusion

This study focuses on the theme of "Ultra-high voltage line UAV inspection technology" and carries out a systematic discussion and analysis. Through a comprehensive review of the technical principles, system composition, key challenges, practical application and future development, the following core conclusions can be drawn:

Drones technology is a revolutionary solution to the challenges of traditional inspection methods for ultra-high voltage (UHV) lines, and it has become an essential direction for intelligent operation and maintenance. Given the large scale, complex environment, and stringent safety requirements of UHV lines, traditional manual inspections face significant limitations in efficiency, safety, coverage, and data accuracy. Drones, with their flexibility, mobility, ability to operate in close proximity, advanced sensors, and reduced personnel risks, effectively address these issues, significantly enhancing the safety, efficiency, precision, and intelligence of UHV line inspections. Practical experience has shown that drone inspections are not only a necessary choice but also a critical path to improving the operational and maintenance capabilities of UHV power grids.

The deep application of technology still faces challenges such as battery life, adaptability to complex environments, strong electromagnetic interference, data processing bottlenecks, and the need for standard talent, requiring a multi-dimensional collaborative response. Currently, there is room for improvement in areas like ultra-long-distance continuous operations, flying in extremely harsh weather conditions, suppressing strong interference in ultra-high voltage environments, real-time intelligent analysis accuracy and efficiency of massive data, as well as the development of composite talents and detailed standards and norms. Overcoming these challenges requires ongoing technological innovation, the establishment of a comprehensive standard system, and the cultivation of specialized talent.

The future development trend clearly points towards higher intelligence, cluster collaboration, deep integration with digital twins, and the expansion of platform functions. Artificial intelligence will drive full-process automation; multi-drone cluster collaboration will overcome the limitations of individual drones; the integration with digital power grids and digital twin technology will enable real-time status perception and predictive maintenance; new power and platform technologies will expand operational boundaries and even empower drones to perform special tasks; an integrated "air-ground-space" monitoring network will create a more robust three-dimensional protection system. Drone line inspection technology will continue to evolve, and its strategic value will become increasingly evident.

In summary, drone patrol technology has opened a new path for the safe and efficient operation and maintenance of ultra-high voltage transmission lines, with its value fully validated in practice. Despite ongoing challenges, the direction of development is clear, and the potential is vast. Through continuous technological advancements, standardization, model innovation, and ecosystem building, drone patrol technology will undoubtedly play an increasingly crucial role in ensuring the safe and stable operation of the nation's energy lifeline and in constructing a new power system centered on renewable energy.

References

1. Z. Wang, Q. Gao, J. Xu and D. Li, "A Review of UAV Power Line Inspection," in *Advances in Guidance, Navigation and Control*, L. Yan, H. Duan and X. Yu, Eds., *Lecture Notes in Electrical Engineering*, vol. 644, Springer, Singapore, 2022. ISBN: 9789811581540.
2. Z. Goraj, A. Frydrychiewicz and J. Winiecki, "Design concept of a high-altitude long-endurance unmanned aerial vehicle," *Aircraft Des.*, vol. 2, no. 1, pp. 19-44, 1999, doi: 10.1016/S1369-8869(99)00004-X.
3. N. Iversen, O. B. Schofield, L. Cousin, N. Ayoub, G. vom Bögel and E. Ebeid, "Design, Integration and Implementation of an Intelligent and Self-recharging Drone System for Autonomous Power line Inspection," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS)*, Prague, Czech Republic, 2021, pp. 4168-4175, doi: 10.1109/IROS51168.2021.9635924.
4. P. K. Rai et al., "Localization and Activity Classification of Unmanned Aerial Vehicle Using mmWave FMCW Radars," *IEEE Sens. J.*, vol. 21, no. 14, pp. 16043-16053, Jul. 2021, doi: 10.1109/JSEN.2021.3075909.

5. T. He, Y. Zeng and Z. Hu, "Research of Multi-Rotor UAVs Detailed Autonomous Inspection Technology of Transmission Lines Based on Route Planning," *IEEE Access*, vol. 7, pp. 114955-114965, 2019, doi: 10.1109/ACCESS.2019.2935551.
6. B. Mendu and N. Mbuli, "State-of-the-Art Review on the Application of Unmanned Aerial Vehicles (UAVs) in Power Line Inspections: Current Innovations, Trends, and Future Prospects," *Drones*, vol. 9, no. 4, p. 265, 2025, doi: 10.3390/drones9040265.
7. A.-M. Muñoz-Gómez, J.-M. Marredo-Píriz, J. Ballestín-Fuertes and J.-F. Sanz-Osorio, "A Novel Charging Station on Overhead Power Lines for Autonomous Unmanned Drones," *Appl. Sci.*, vol. 13, no. 18, p. 10175, 2023, doi: 10.3390/app131810175.
8. R. P. Padhy et al., "Deep neural network for autonomous UAV navigation in indoor corridor environments," *Procedia Comput. Sci.*, vol. 133, pp. 643-650, 2018, doi: 10.1016/j.procs.2018.07.099.
9. M. Xu, "Research on 5G UAV Smart Grid Inspection Technology Based on Digital Twin," in *Proc. IEEE Int. Conf. Cloud Comput. Intell. Syst. (CCIS)*, Xi'an, China, 2021, pp. 367-370, doi: 10.1109/CCIS53392.2021.9754652.
10. Z. Li, Y. Zhang, H. Wu, S. Suzuki, A. Namiki and W. Wang, "Design and Application of a UAV Autonomous Inspection System for High-Voltage Power Transmission Lines," *Remote Sens.*, vol. 15, no. 3, p. 865, 2023, doi: 10.3390/rs15030865.
11. T. Zhang, Q. Li, Cs. Zhang et al., "Current trends in the development of intelligent unmanned autonomous systems," *Front. Inf. Technol. Electron. Eng.*, vol. 18, pp. 68-85, 2017, doi: 10.1631/FITEE.1601650.
12. Q. Du, W. Dong, W. Su and Q. Wang, "UAV Inspection Technology and Application of Transmission Line," in *Proc. IEEE Int. Conf. Inf. Syst. Comput. Aided Educ. (ICISCAE)*, Dalian, China, 2022, pp. 594-597, doi: 10.1109/ICISCAE55891.2022.9927674.