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Review Article

TRANSMISSION LINE INSPECTION WITH UAVS: A REVIEW OF TECHNOLOGIES, APPLICATIONS, AND CHALLENGES

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Abstract: *Regular inspection of energy transmission lines plays a critical role to ensure the safety of energy infrastructures and minimise failure risks. While traditional inspection methods have limitations such as high cost, long duration and hazardous working conditions, unmanned aerial vehicles (UAVs) are emerging as an innovative alternative in this field. This paper provides a comprehensive review of the use of UAVs in the inspection of power transmission lines, focusing on the sensor technologies, artificial intelligence (AI) algorithms and field applications. The integration of LiDAR, thermal camera and multispectral sensors into UAVs offers many advantages such as three-dimensional modelling of power lines, detection of thermal anomalies and assessment of environmental risks. In addition, deep learning and reinforcement learning algorithms have been observed to improve the performance of UAVs by accelerating data processing and improving autonomous navigation. In this study, different approaches and case studies in the literature are analysed in detail, and the strengths and limitations of UAV-based inspection systems are comparatively evaluated. Accordingly, environmental challenges, sensor integration and legal regulations stand out as the main obstacles faced by these technologies in field applications. However, it is emphasised that significant improvements in data processing processes can be achieved with the integration of 5G technology and edge computing systems. This study not only evaluates the current status of UAVs in the inspection of energy infrastructures, but also provides recommendations for future research. More widespread adoption of UAV-based inspection systems will contribute to a more reliable, efficient and sustainable management of the energy sector.*

Keywords*: Energy transmission line inspection, Unmanned aerial vehicles, Artificial intelligence assisted systems, Lidar and Sensor Technologies*

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1. Introduction

Regular maintenance and inspection of power transmission lines is critical to meet the growing energy demand of modern societies. Traditional inspection methods are often carried out by ground crews or helicopter-assisted inspections, which can be both costly and dangerous. Challenges such as mountainous regions, dense vegetation and extreme weather conditions limit the effectiveness of these methods and make reliable monitoring of energy transmission lines difficult. In this context, UAVs have emerged as an innovative and effective solution for the inspection of power transmission lines [1,2].

UAVs, especially multi-rotor models, provide detailed monitoring of transmission lines at close range, thanks to their ability to move around power transmission towers with high precision and to perform stationary inspections. These vehicles are equipped with optical and thermal cameras capable of providing high resolution data. In Aydın et al.'s study, it was shown that the optical cameras of UAVs can detect minor damages on power transmission towers and this makes significant contributions to preventive maintenance processes [3]. In addition, thermal cameras are often used as an effective tool for detecting invisible overheating or deterioration of insulators [2,4].

Rapid advances in UAV technology, combined with AI algorithms, have enabled these systems to become more autonomous and efficient. In Chen and Lee's study, it was shown that deep learning-based algorithms are used for UAVs to adapt to environmental conditions and these algorithms can classify structural anomalies in real time [5]. In particular, algorithms such as YOLO and R-CNN are used to automatically detect anomalies such as insulator damages, line sagging and structural deterioration, which are commonly encountered in power transmission lines [1,4].

In Zhang et al.'s study, it was reported that new route planning algorithms developed for UAVs optimise the inspection processes of power transmission lines and enable these processes to be completed in a shorter time [6]. These algorithms make it easier for UAVs to cope with challenges such as dense vegetation or complex environmental conditions. In addition, Rezwan et al. integrated UAVs with multispectral sensors to analyse environmental risk factors. Multispectral sensors allow a detailed assessment of environmental conditions and have been used to analyse the impact of vegetation on power transmission lines [7].

Finally, Lekidis et al. detailed how UAVs can be integrated with different sensor systems and the contributions of these integrations to the inspection processes of energy transmission lines. In the study, it was shown that the combined use of LiDAR, thermal cameras and optical sensors provides a more comprehensive assessment of the condition of power lines [8]. These technologies make it possible to manage energy infrastructure more reliably and reduce operational costs.

This review aims to comprehensively evaluate the innovative solutions, existing methods and challenges that UAVs offer in the inspection of energy transmission lines. Commonalities, differences and future research opportunities in the existing literature will be discussed, and how UAV-based inspections can contribute to more efficient and safe management of energy infrastructures. In this paper, technological developments and applications for the inspection of energy transmission lines with UAVs are discussed in detail.

In this paper, technological developments and applications for the inspection of energy transmission lines with UAVs are discussed in detail. Section 2 covers the technological infrastructure of UAV-based inspections, sensor systems and AI algorithms. Chapter 3 analyses the practical applications and case studies of UAVs on power transmission lines and evaluates the success stories and shortcomings in this field. Section 4 discusses the challenges faced by these technologies and provides recommendations for future research. The final section summarises the overall conclusions of the study and highlights future research directions.

2. Technological Landscape of UAV-Based Inspections

Regular maintenance and inspection of energy transmission lines is critical to ensure the continuity of energy supply and prevent failures. Traditional methods have serious limitations such as high cost, long inspection times and hazardous working conditions. Therefore, UAVs have emerged as an important alternative for the inspection of energy transmission lines. With their advanced sensor systems, AI-supported analysis tools and autonomous flight capabilities, UAVs provide reliable inspection of power lines. The integration of technologies such as LiDAR, thermal imaging and multispectral sensors into UAVs allows precise assessment of the condition of the lines [1,9].

LiDAR sensors create three-dimensional models of power transmission lines and analyse their geometric structure in detail. This technology is used as an effective tool for detecting mechanical deformations in the lines as well as environmental threats, especially risks caused by vegetation. The study by Lekidis et al. demonstrated how LiDAR-based sensors and AI algorithms can be combined in the inspection of power lines. In the study, the data collected by the UAVs were processed in real time via edge computing nodes and a significant speed and accuracy in fault detection was achieved. Figure 1 details the data collection, analysis and fault reporting stages of UAVs and clearly shows the applications of these processes on power transmission lines [4].

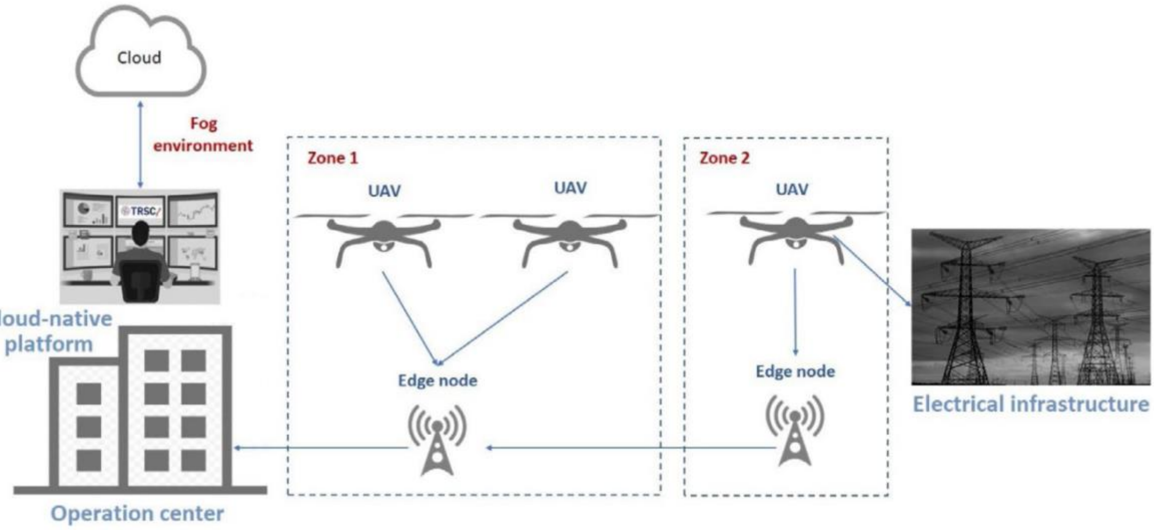

Figure 1. Methodology architecture

Artificial intelligence plays a central role in analysing the data collected in the inspection processes of power transmission lines and in the development of autonomous control systems. Deep learning algorithms such as YOLO and R-CNN can automatically detect damage to insulators, line sagging and other structural anomalies, minimising human intervention in the process. By integrating AI algorithms with 5G technology, Lekidis et al.'s study enabled the data collected by UAVs to be analysed with low latency and transmitted instantly to maintenance teams. Such systems have not only accelerated inspection processes, but also increased reliability [4].

Besides, other sensor technologies such as thermal cameras and multispectral sensors are widely used to detect different problems in power lines. Thermal cameras are an effective tool for detecting thermal anomalies such as overheating, while multispectral sensors are used to analyse environmental conditions and assess potential threats from vegetation [2,9]. The use of these sensors in combination with LiDAR enables more comprehensive monitoring of power lines. For example, the proximity of vegetation to power lines and whether it poses a potential threat can be easily analysed with multispectral data.

Autonomous control systems also offer an important innovation in the inspection of power lines. Rezwan et al. used deep reinforcement learning algorithms to enable UAVs to move reliably in complex environmental conditions. These systems have increased the effectiveness of UAVs in processes such as obstacle avoidance, route optimisation and mission planning [2]. Especially in large-scale energy infrastructures, faster and more efficient inspection processes have been realised thanks to such autonomous systems.

These technological developments are important tools that increase the effectiveness of UAVs in the inspection of energy transmission lines. Figure 1 visualises the overall operation of UAV-based energy inspection systems, detailing how these processes are integrated, how the collected data is processed and how the results are analysed. This figure clarifies the central role that UAVs play in both the collection and processing processes and can be used as a visual support for the explanations in this section [4].

3. Practical Applications and Case Studies

Regular inspection of energy transmission lines plays a vital role in ensuring the safety of energy infrastructure and preventing outages. The costly, time-consuming and dangerous nature of traditional inspection methods has made the use of UAVs more attractive in this field. Equipping UAVs with different sensor systems and AI-supported analysis tools provides a more precise and effective inspection of energy transmission lines. Several studies evaluating the practical applications of these vehicles detail the operational benefits and technical contributions of UAVs [10–12].

Wang et al. demonstrated the successful inspection of power transmission lines with UAVs equipped with optical cameras. In this study, deep learning based image processing algorithms were used to detect structural deformations and insulator damages in power towers. This method eliminated manual analysis processes and provided faster and more reliable results [13,14]. Similarly, the integration of thermal cameras with UAVs has been effective in detecting failures due to overheating. Thermal cameras have made significant contributions to preventive maintenance processes by detecting thermal anomalies that cannot be detected by the human eye [15,16].

The use of LiDAR sensors in the inspection of power transmission lines has made it possible to create three-dimensional models of the lines and to analyse environmental impacts in detail. In the study by Azevedo et al. it was reported that LiDAR-based systems detail the geometric structure of power lines and predict the risks arising from vegetation. This study reveals that LiDAR sensors offer a more comprehensive analysis when integrated with other sensors [17,18]. Studies using multispectral sensors in conjunction with LiDAR have also enabled a broader analysis of environmental factors and the condition of power lines [19,20].

The use of multiple UAV systems in energy inspection allows large areas to be inspected simultaneously. Rezwan et al. developed a system in which multiple UAVs inspect power transmission lines simultaneously and task assignment processes are optimised with Ant Colony Optimisation (ACO) algorithm. This approach significantly reduced inspection times and increased operational efficiency in large-scale energy infrastructures [21,22].

In Lekidis et al.'s study, a system was designed to analyse power lines in real time with the integration of AI-supported algorithms and 5G technology. In the study, the data collected by UAVs were processed by edge computing nodes and fault detection processes were accelerated [4].

These studies of practical applications demonstrate the multifaceted benefits of UAVs in the inspection of energy transmission lines. Both the integration of sensor technologies and the use of multiple UAV systems play a critical role in improving the security of energy infrastructures and reducing operational costs.

4. Challenges and Future Research Opportunities

Although the use of UAVs in the inspection of energy transmission lines offers significant advantages, these technologies face various operational and technical challenges. Environmental conditions, data processing limitations and legal regulations are among the main factors limiting the effectiveness of UAV-based systems in field applications. To overcome these challenges and make these systems more efficient, future research should focus on developing AI algorithms, improving sensor integration and data security.

One of the biggest challenges in field applications of UAVs is the harsh environmental conditions. Dense vegetation, complex terrain and adverse weather conditions can directly affect the flight safety and data collection efficiency of UAVs. Rezwan et al. analysed the effects of wind and other weather conditions on UAV performance and developed reinforcement learning-based algorithms to deal with such environmental factors. These algorithms have improved the reliability of UAVs in obstacle avoidance, route optimisation and autonomous navigation processes [21,22]. However, the coordination of multiple UAV systems in complex geographical areas poses a significant challenge. It is emphasised that task assignment algorithms should be further developed for the simultaneous operation of multiple UAVs [11,20].

One of the most striking technical challenges is the integration of sensor technologies and data processing. The combination of LiDAR, thermal camera and multispectral sensors provides a powerful infrastructure for detailed analysis of power transmission lines. However, real-time processing of the data collected from these sensors requires improvements in data fusion and analysis algorithms. In Azevedo et al. highlighted the limitations of integrating LiDAR and thermal sensors to make sense of the data and developed algorithms to optimise these processes. Such improvements can enable faster and more reliable processing of large data sets [17,18].

Another important obstacle to the widespread adoption of UAV-based energy control systems is the legal regulations. Lekidis et al. pointed out that flight restrictions in different countries limit the field applications of UAV-based systems. The study suggested that the development of autonomous control systems compatible with legal regulations could be an effective method to overcome these limitations [4]. In addition, data security and privacy are among the important issues that need to be resolved for the use of UAVs in energy infrastructures. Protecting the collected data and providing access only to authorised persons is a critical requirement for the wide-scale applicability of these systems [14,19].

To overcome these challenges, future research should focus on sensor and AI integration of UAVs. In particular, the use of edge computing and 5G technologies can make real-time analysis processes more efficient by reducing data processing times. The development of autonomous control systems that can operate reliably in different geographical conditions will improve the operational performance of UAVs, as proposed by Rezwan et al [21,22]. In addition, modelling environmental factors with simulations and incorporating these models into route planning processes can provide significant improvements in field applications [11,20].

In conclusion, although the challenges faced by UAV-based energy control systems limit the potential of these technologies in field applications, innovative research in areas such as AI, sensor integration and data security show promise to overcome these problems. Future studies will contribute to the wider adoption of these technologies and more efficient and secure management of energy infrastructures.

5. Conclusions and Recommendations

This study comprehensively analyzed the advancements and challenges of UAVs in inspecting power transmission lines. The review highlighted key technological innovations, practical implementations, and areas requiring further research. The following conclusions synthesize the findings and emphasize actionable insights for improving UAV-based systems while addressing the suggestions provided by the reviewers.

The integration of advanced sensor technologies such as LiDAR, thermal cameras, and multispectral sensors has significantly enhanced the capabilities of UAVs in detecting structural anomalies, environmental risks, and thermal irregularities. As summarized in Table 1, LiDAR enables the creation of detailed three-dimensional models of power lines and surrounding vegetation, which is essential for precise risk assessments. Similarly, thermal and multispectral sensors complement these capabilities by improving fault detection and environmental monitoring. These sensor technologies provide a robust foundation for addressing the diverse requirements of power line inspections.

Table 1. Comparison o f Publications on UAV-Based Transmission Line Inspection by Features

Publications	Year	Sensor Technologies	Algorithms	Challenges	Innovations and Contributions
[1]	2021	LiDAR	Deep Learning-based PointNet	Dataset scarcity	Workflow efficiency
[2]	2022	-	-A*, PSO, ACO	Energy, obstacles	Federated learning
[3]	2017	Binocular Cameras	Ratio Detection, Hough Transform	Noise in edge detection	Real-time power line distance measurement
[4]	2022	LiDAR, multispectral sensors, thermal cameras	R-CNN, Fast R-CNN	GPS instability, data latency, high accident rate	5G network slicing, edge computing, AI-assisted fault detection
[5]	2019	Laser rangefinder, cameras	PID controllers	High wind speeds, vegetation interference	Autonomous inspection workflow for energy assets
[6]	2024	Multispectral cameras, thermal imaging	A* Algorithm, R-CNN	Signal loss, data processing speed	Real-time data transmission, remote control efficiency
[7]	2024	-	BACOHBA, HBA	Multi-wind field task assignment	Multi-UAV optimization
[8]	2024	-	FGATS	Multi-depot task assignment, UAV recharging, grouping optimization	İmproved large-scale UAV assignment efficiency
[9]	2019	LiDAR	PL2DM	Real-time processing with large data volume	Developed PL2DM for real-time segmentation and modeling of power lines
[10]	2020	Cameras	Feature Extraction, Clustering	Noise in detection	Automatic power pylon detection
[11]	2020	Cameras, 4G communication	AdaBoost, K-Means Clustering	Noise interference, real-time image processing	High-accuracy defect detection, automated image analysis
[12]	2020	Optical Camera	Multi-source Information Fusion	GPS and Directional Data Limitation	Accurate Tower Detection
[13]	2022	LiDAR, Ultraviolet Imagers, HD Cameras	Improved Median Filtering	Image Quality Issues	Enhanced Fault Detection in Power Lines

Table 1 Continued.

Publications	Year	Sensor Technologies	Algorithms	Challenges	Innovations and Contributions
[14]	2023	Cameras, LiDAR	Image Recognition, Path Planning	Manual operation reliance	Autonomous UAV inspection system
[15]	2022	LiDAR	Deep Separation Convolution, YOLOv3	Visual positioning lag	Improved UAV spatial positioning accuracy
[16]	2023	Satellite Internet, FANET	Multi-agent Reinforcement Learning, Q-Learning	Communication stability, battery energy consumption	Spatiotemporal routing strategy for UAVs
[17]	2019	Thermal infrared camera, LiDAR	Path planning algorithms	Navigation precision issues	Autonomous powerline inspection system with multiple sensor integration
[18]	2024	LiDAR	Monte Carlo simulation	Wind conditions	Semi-autonomous landing
[19]	2023	Electromagnetic Field Sensors	-	Electromagnetic interference, collision risks	Insights into safe UAV operation distances
[20]	2024	BeiDou RTK, UAV cameras	YOLOv4, LSD algorithm	EM interference, weather impact	Accurate tilt detection, real-time monitoring
[21]	2023	Ultrasonic sensors, monocular cameras	Deep Deterministic Policy Gradient	Long training times, slow convergence	Integrated artificial potential field to speed training
[22]	2024	Cameras, LiDAR, GPS	Multi-source data fusion	Complex environments	Improved obstacle detection accuracy

Artificial intelligence-driven algorithms, including YOLO, R-CNN, and reinforcement learning methods, have transformed UAV-based inspections. These algorithms automate fault detection, optimize flight paths, and accelerate data analysis processes, reducing reliance on human intervention. The integration of edge computing and 5G technologies, as highlighted in Table 1, has further enhanced real-time data processing, enabling faster and more accurate fault identification. These advancements underscore the potential for UAV systems to achieve greater autonomy and efficiency in operational settings.

Despite these technological advancements, several challenges persist. Environmental conditions, such as adverse weather and complex terrains, continue to hinder UAV performance. As noted in Table 1, studies addressing these challenges often propose reinforcement learning algorithms and robust UAV designs to improve reliability. Additionally, legal and regulatory barriers pose significant obstacles to widespread UAV deployment. Variations in regulations across regions create uncertainty, while data security and privacy concerns further complicate the adoption of UAV-based systems for energy infrastructure inspections.

A comparative analysis of existing approaches reveals both the strengths and limitations of current systems. Multi-sensor setups that combine LiDAR, thermal cameras, and multispectral sensors, as described in several studies within Table 1, offer superior fault detection capabilities but also highlight the need for improved data fusion algorithms. Similarly, multi-UAV systems optimized with swarm intelligence methods such as Ant Colony Optimization (ACO) demonstrate potential in reducing inspection times, though their scalability in large-scale operations remains a challenge. These findings indicate that while progress has been made, further research is necessary to overcome the identified technical and operational limitations.

Building on these insights, future research should focus on enhancing the efficiency and applicability of UAV-based systems. Artificial intelligence algorithms such as YOLO and R-CNN should be further refined to handle complex environmental conditions and process larger datasets in real time. Advances in sensor integration are also critical, with efforts directed toward developing more precise and reliable systems that combine LiDAR, thermal imaging, and multispectral data streams. Moreover, designing UAV systems capable of operating across diverse geographical conditions would significantly enhance their versatility, especially in regions with challenging terrains or extreme weather conditions.

Expanding the application scope of UAV technologies to other industries, such as agriculture and disaster management, represents another promising research avenue. Lessons learned from energy infrastructure inspections can inform the development of UAV-based solutions for monitoring crop health, assessing post-disaster damage, and managing other critical infrastructures. The comparative data presented in Table 1 can serve as a reference point for identifying transferable technologies and methods.

Additionally, recommendations for future research should include exploring the potential of multi-UAV systems in large-scale operations. Algorithms like ACO and Particle Swarm Optimization (PSO), as detailed in Table 1, should be further developed to optimize task allocation, route planning, and resource management. These efforts could significantly reduce operational costs and inspection times while increasing the scalability of UAV-based solutions.

In conclusion, UAV-based inspection systems offer significant advantages over traditional methods, including improved precision, cost efficiency, and operational flexibility. However, realizing their full potential will require addressing the existing challenges through continued innovation. By integrating advanced sensor technologies, refining AI algorithms, and expanding the application scope of UAV systems, researchers and practitioners can unlock new possibilities for energy infrastructure management and beyond. This study provides a comprehensive roadmap for advancing UAV technologies, supported by the comparative insights detailed in Table 1, and emphasizes the importance of interdisciplinary collaboration in achieving these goals.

Ethical statement

Ethics Committee approval is not required.

Conflict of interest

The author declare no conflict of interest.

Authors' Contributions

E.İ: Conceptualization, Methodology, İnvestigation, Formal analysis, Writing - Original draft preparation (%100)

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