

A Review of UAV Applications in Electrical Transmission Line Inspection: Methods, Technologies, and Challenges

DELALI DAGODZO
GEOLOG International, Accra, Ghana

Abstract- This paper presents a comprehensive review of unmanned aerial vehicle applications in electrical transmission line inspection, focusing on methods, enabling technologies, and operational challenges. Traditional inspection techniques, including ground-based surveys and manned helicopter patrols, are often costly, time-consuming, and hazardous, thereby necessitating more efficient alternatives. UAV-based inspection systems have emerged as transformative solutions, offering enhanced accessibility, real-time data acquisition, and improved safety performance. The study examines key inspection methods, including visual imaging, infrared thermography, LiDAR-based scanning, and multispectral sensing, which enable fault detection, vegetation monitoring, and structural assessment. It further explores technological advancements in UAV platforms, such as autonomous navigation, artificial intelligence-driven image processing, and integration with geographic information systems for predictive maintenance. Despite these advancements, several challenges persist, including limited flight endurance, regulatory constraints, data processing complexity, cybersecurity risks, and environmental factors affecting flight stability. The review highlights the need for robust communication systems, advanced battery technologies, and standardized regulatory frameworks to support large-scale deployment. Additionally, the paper identifies emerging research directions, including swarm UAV coordination, edge computing, and digital twin integration for smart grid applications. By synthesizing current knowledge and technological trends, this review provides valuable insights for researchers, industry practitioners, and policymakers seeking to optimize transmission line inspection processes and enhance power system reliability. The findings underscore the critical role of UAVs in modernizing infrastructure monitoring while emphasizing the importance of addressing technical and regulatory limitations to achieve sustainable and scalable implementation across diverse energy environments. Furthermore the integration of machine learning models enhances defect classification accuracy and reduces manual interpretation efforts in large-scale inspection datasets. Economic considerations, including cost-benefit

analysis and lifecycle optimization, demonstrate the potential of UAV systems to significantly lower operational expenditures compared to conventional inspection approaches. However, issues related to data standardization, interoperability, and workforce skill gaps remain critical barriers to widespread adoption. Addressing these limitations requires multidisciplinary collaboration among engineers, regulators, and energy stakeholders to develop resilient and adaptive inspection frameworks. Ultimately, this review establishes a foundation for future innovations aimed at achieving intelligent, autonomous, and data-driven inspection ecosystems within modern power transmission networks, ensuring improved efficiency, safety, and operational resilience globally.

Keywords: UAV, Transmission Line Inspection, LiDAR, Thermography, Artificial Intelligence, Smart Grid, Predictive Maintenance, Drone Technology

I. INTRODUCTION

Electrical transmission line inspection is a critical component of power system maintenance, ensuring the reliability, safety, and efficiency of electricity delivery across vast and often challenging terrains. Transmission networks form the backbone of modern energy systems, and their continuous operation is essential for economic stability, industrial productivity, and societal well-being (Anioke & Atima, 2018, Badmus & Olamide, 2018). Regular inspection of transmission lines enables early detection of faults such as conductor damage, insulator degradation, corrosion, and vegetation encroachment, which, if left unaddressed, can lead to power outages, equipment failure, or catastrophic incidents. Consequently, utilities and grid operators prioritize inspection regimes as part of preventive and predictive maintenance strategies aimed at enhancing system resilience and minimizing operational risks (Congress, 2018, Ton & Wang, 2015).

Despite their importance, traditional inspection methods present significant limitations. Manual inspections, which involve ground patrols or climbing structures, are labor-intensive, time-consuming, and expose personnel to considerable safety hazards, including falls, electrical risks, and harsh environmental conditions. Similarly, helicopter-based inspections, while offering broader coverage, are associated with high operational costs, limited maneuverability in confined or complex terrains, and increased environmental impact due to fuel consumption and emissions. Both approaches often suffer from inconsistencies in data quality, reliance on human judgment, and limited capability for detailed or repeatable analysis, thereby constraining their effectiveness in modern, data-driven asset management systems (Aransi, et al., 2018, Farounbi, et al., 2018, Odejobi & Ahmed, 2018).

In recent years, unmanned aerial vehicles have emerged as transformative tools in electrical transmission line inspection. UAVs provide a flexible, cost-effective, and safer alternative, capable of accessing remote or hazardous locations while capturing high-resolution data in real time. Equipped with advanced sensors such as optical cameras, infrared thermography systems, and LiDAR, UAVs enable precise detection of faults and support comprehensive condition assessment. Their integration with artificial intelligence and geospatial technologies further enhances automated analysis, enabling utilities to transition toward intelligent and predictive maintenance frameworks within evolving smart grid environments (Mohl, 2016, Tudevtagva, et al., 2017).

This review aims to synthesize current knowledge on UAV applications in transmission line inspection, focusing on inspection methods, enabling technologies, and associated challenges. It critically examines the capabilities and limitations of UAV-based systems while identifying gaps and opportunities for future research and development. The study is structured to first provide an overview of UAV systems and inspection methodologies, followed by an analysis of technological advancements, practical applications, and operational challenges. It concludes with insights into emerging trends and recommendations for advancing UAV-enabled

inspection practices in modern power systems (Masum, 2018, Moore, et al., 2017).

2.1. Methodology

For this study, a PRISMA-informed systematic review methodology is the most suitable approach because the topic is evidence-based, technology-driven, and multidisciplinary, drawing from engineering, remote sensing, robotics, power systems, and data analytics literature. The methodology is designed to provide a structured, transparent, and reproducible synthesis of existing knowledge on UAV applications in electrical transmission line inspection, with particular attention to inspection methods, enabling technologies, operational applications, and implementation challenges. The review begins by defining the problem context and formulating focused review objectives. The central aim is to examine how UAV systems have been applied in electrical transmission line inspection, what sensing and computational technologies enable these applications, what practical benefits have been reported, and what technical, regulatory, and operational constraints continue to affect deployment. The review is therefore guided by questions relating to the types of UAV platforms used, the inspection methods adopted, the role of sensors such as cameras, thermography, and LiDAR, the contribution of automation and analytics, and the major gaps that require future research attention.

The literature identification stage is built around the reference base supplied for the study, which serves as the seed corpus for source selection. From this foundation, the review proceeds through a structured search and snowballing process. Studies directly related to UAV-based power line inspection, autonomous aerial monitoring, inspection data processing, remote sensing for corridor monitoring, communications for UAV inspection, and smart-grid integration are prioritized. Relevant works include foundational studies on UAV-based power line inspection and cooperative communications, automated inspection systems, vision-based inspection, photogrammetry, path-conformance autonomy, LiDAR geofencing, and energy-efficient industrial UAV systems. Additional supporting literature is drawn from references on analytics, big data architectures, dataflow systems, decision support,

process modeling, remote sensing, and risk assessment because these provide methodological grounding for understanding how inspection data are acquired, processed, interpreted, and operationalized in transmission infrastructure contexts. Backward and forward snowballing are then applied to identify further directly relevant studies cited by, or citing, the seed papers, ensuring adequate conceptual and technical coverage of the domain.

Eligibility criteria are established before screening to improve rigor and reduce selection bias. Included studies are those that focus substantially on UAV applications in electrical transmission line inspection or immediately related inspection tasks in utility corridors. These include peer-reviewed journal articles, reputable conference papers, technical reports, theses, and high-value conceptual studies where they contribute to explaining platforms, sensors, inspection workflows, autonomy, communication systems, analytics, maintenance use cases, or implementation barriers. Studies are retained if they address one or more of the following: UAV classification and deployment for line inspection, sensing technologies, defect detection methods, data transmission and processing systems, automation and artificial intelligence in inspection, regulatory integration, or infrastructure resilience implications. Studies are excluded where UAVs are discussed in unrelated domains without transferable inspection relevance, where the focus is too general and not sufficiently connected to power infrastructure, or where duplicated entries provide no added analytical value. Because the supplied bibliography includes a few duplicated or broadly adjacent sources, deduplication and relevance filtering are necessary parts of the method.

Screening is conducted in three progressive stages: title review, abstract review, and full-text eligibility assessment. During title screening, obviously irrelevant studies are removed. Abstract screening then evaluates topical alignment with the review questions. Full-text screening is used to confirm whether each publication contains sufficient methodological, technological, or application-oriented detail to contribute meaningfully to the synthesis. At this stage, the final sample is assembled. To maintain consistency, each selected paper is reviewed using a

structured extraction matrix. The extraction form captures bibliographic information, publication year, study type, inspection context, UAV platform category, onboard sensors, communication architecture, navigation or autonomy features, data processing techniques, defect or condition targets, application outcomes, stated limitations, and future recommendations. Where studies report comparative performance, these findings are also recorded, especially in areas such as flight endurance, image quality, detection accuracy, coverage efficiency, and operational feasibility.

Given the review nature of the study, data analysis is conducted through thematic synthesis rather than statistical meta-analysis. A qualitative coding framework is developed to organize extracted evidence into major domains consistent with the study objectives. These domains include overview of UAV systems in power infrastructure, inspection methods using UAVs, enabling technologies and innovations, applications in transmission line inspection, operational and technical challenges, regulatory and economic issues, and future directions. Within these domains, subthemes are coded iteratively, such as fixed-wing versus rotary-wing suitability, visual versus thermal inspection, LiDAR mapping, AI-based defect detection, communication reliability, battery limitations, cybersecurity issues, and smart-grid integration. Comparative reading is then used to identify patterns of agreement, divergence, maturity, and emerging innovation across the literature. This method is especially useful because the field contains mixed evidence types, including experimental demonstrations, conceptual system proposals, applied case studies, and review articles.

To strengthen methodological trustworthiness, a quality appraisal step is included. Each selected study is assessed against practical criteria such as clarity of objectives, adequacy of technical description, appropriateness of inspection method, transparency of system architecture, evidential strength of reported outcomes, and relevance to transmission line inspection practice. Studies with stronger empirical grounding and clearer methodological disclosure are weighted more heavily in the narrative synthesis, while conceptual or exploratory papers are used primarily to frame innovation pathways and future

possibilities. This approach allows the review to remain inclusive without treating all sources as equally evidential.

The synthesis stage integrates findings across all coded themes to produce an evidence-based narrative of the field. Rather than merely listing studies, the methodology supports analytical comparison of how inspection systems are designed, what technologies are most frequently deployed, which operational use cases are most mature, and what limitations recur across contexts. It also enables the study to trace the progression of the field from manually piloted visual inspections toward more autonomous, sensor-rich, data-intensive, and analytics-enabled inspection ecosystems. The final output of the methodology is therefore a structured review that not only summarizes existing knowledge but also identifies research gaps, implementation bottlenecks, and strategic opportunities for advancing UAV-enabled transmission line inspection in modern power systems.

power infrastructure, UAVs have become essential tools for monitoring, inspection, and maintenance of electrical transmission networks. Their classification is primarily based on aerodynamic design and operational capabilities, which include fixed-wing, rotary-wing, and hybrid systems. Fixed-wing UAVs resemble conventional aircraft and are characterized by their ability to cover long distances with high energy efficiency, making them suitable for large-scale corridor inspections (Islam, Ahmed & Islam, 2018, Musavi, et al., 2017). Rotary-wing UAVs, including quadcopters and hexacopters, offer vertical take-off and landing capabilities, high maneuverability, and the ability to hover, which are critical for detailed inspection tasks around towers and conductors. Hybrid UAVs combine the endurance of fixed-wing platforms with the flexibility of rotary systems, allowing both long-range flight and localized hovering, thereby offering a balanced solution for diverse inspection requirements (Odejobi & Ahmed, 2018, Seyi-Lande, Arowogbadamu & Oziri, 2018).

The effectiveness of UAV systems in power infrastructure inspection is largely determined by their onboard components, which enable data acquisition, communication, and navigation. Sensors are central to UAV functionality and typically include high-resolution optical cameras for visual inspection, infrared thermographic cameras for detecting hotspots and thermal anomalies, and LiDAR systems for generating accurate three-dimensional representations of transmission corridors. In addition, multispectral and hyperspectral sensors can be employed for advanced material analysis and vegetation monitoring (Jordan, et al., 2018, Zhou, et al., 2018). Communication systems facilitate real-time data transmission between the UAV and ground control stations, often using radio frequency links, satellite communication, or cellular networks depending on operational range and environmental conditions. Reliable communication is essential for both control commands and the transfer of large volumes of inspection data. Navigation units, which include global navigation satellite systems such as GPS, inertial measurement units, and onboard processors, enable precise positioning, flight stability, and autonomous route execution. These components work in synergy to ensure that UAVs can perform complex inspection missions with high accuracy and

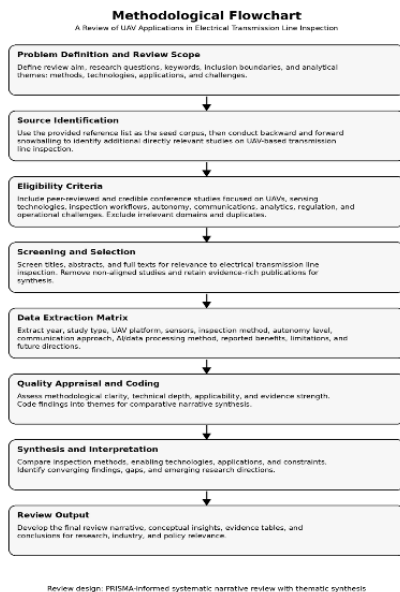


Figure 1: Flowchart of the study methodology

2.2. Overview of UAV Systems in Power Infrastructure

Unmanned aerial vehicles, commonly referred to as UAVs or drones, are aerial platforms that operate without an onboard human pilot and are either remotely controlled or capable of autonomous flight through embedded control systems. In the context of

repeatability (Ahmed & Odejebi, 2018, Nwafor, et al., 2018, Seyi-Lande, Arowogbadamu & Oziri, 2018).

The operational principles of UAV deployment in electrical transmission line inspection are based on systematic mission planning, data acquisition, and post-processing workflows. Prior to deployment, flight paths are carefully designed to follow transmission corridors while maintaining safe distances from conductors and structures. Autonomous navigation systems allow UAVs to execute predefined routes, while obstacle detection and avoidance technologies enhance operational safety. During flight, UAVs capture high-resolution imagery and sensor data, which can be analyzed in real time or stored for subsequent processing (Mitchell, Rosenqvist & Mora, 2017, Stow, et al., 2018). The ability to hover and adjust flight parameters enables detailed inspection of critical components such as insulators, connectors, and tower structures. Post-flight data processing involves image stitching, point cloud generation, and integration into geospatial platforms, enabling comprehensive analysis and decision-making. This structured approach enhances inspection accuracy and reduces the likelihood of missed defects compared to traditional methods. Figure 2 shows figure of UAV used for power line inspection presented by Luque-Vega, et al., 2014.

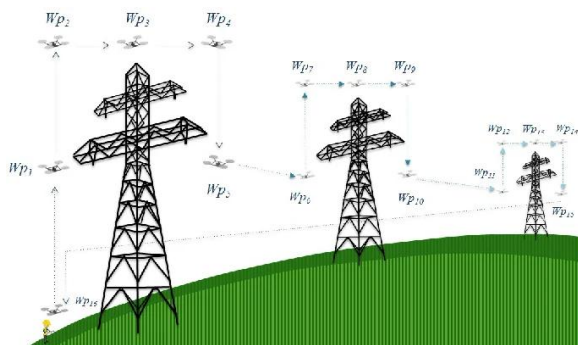


Figure 2: UAV used for power line inspection (Luque-Vega, et al., 2014).

A comparative assessment of UAV types reveals that each platform offers distinct advantages and limitations in transmission line inspection. Fixed-wing UAVs are highly efficient for covering extensive transmission corridors due to their longer flight endurance and higher speeds. However, their inability to hover and requirement for runway or catapult launch systems limit their effectiveness in detailed

inspections. Rotary-wing UAVs, on the other hand, excel in close-range inspection tasks, providing high-resolution data through stable hovering and precise maneuvering. Their shorter flight time and limited range, however, make them less suitable for large-scale inspections without frequent battery changes (Karsenti & Daguzan, 2017, Sampigethaya, Kopardekar & Davis, 2018). Hybrid UAVs address these limitations by integrating vertical take-off and landing capabilities with extended flight endurance, offering a versatile solution for both corridor mapping and detailed asset inspection. The selection of UAV type is therefore dependent on inspection objectives, terrain characteristics, and operational constraints.

In modern smart grid systems, UAVs play a pivotal role in enabling intelligent, data-driven infrastructure management. Smart grids rely on real-time data, automation, and advanced analytics to optimize energy distribution and enhance system resilience. UAVs contribute to this paradigm by providing timely and high-quality data that supports condition-based monitoring and predictive maintenance strategies. Their integration with artificial intelligence and machine learning algorithms allows for automated defect detection and classification, reducing reliance on manual interpretation and improving operational efficiency (Gu, Michanowicz & Jia, 2018, Smethurst, et al., 2017). Furthermore, UAV-generated data can be integrated with geographic information systems and digital twin models to create dynamic representations of transmission networks, facilitating proactive decision-making and resource optimization.

The adoption of UAV systems also supports rapid response during emergency situations, such as storms, equipment failures, or natural disasters. UAVs can be deployed quickly to assess damage, identify affected areas, and support restoration efforts, thereby minimizing downtime and improving service reliability. In addition, their use reduces the need for human intervention in hazardous environments, enhancing worker safety and reducing operational risks. As power systems continue to evolve toward greater complexity and digitalization, UAVs are expected to play an increasingly significant role in supporting infrastructure resilience and sustainability. Figure 3 shows a functional diagram of the LiDAR

technology that provides accurate ranging for UAS operations presented by Ogan, Lott & Paden, 2019.

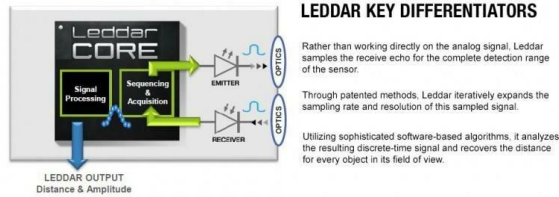


Figure 3: A functional diagram of the LiDAR technology that provides accurate ranging for UAS operations (Ogan, Lott & Paden, 2019).

Overall, UAV systems represent a transformative advancement in the inspection and management of electrical transmission infrastructure. Their diverse configurations, advanced onboard technologies, and integration with smart grid systems position them as indispensable tools for modern power utilities. By addressing the limitations of traditional inspection methods and enabling more efficient, accurate, and safe operations, UAVs are reshaping the future of transmission line inspection and contributing to the development of more reliable and intelligent energy systems (Mueller, Kopardekar & Goodrich, 2017).

2.3. Inspection Methods Using UAVs

Inspection methods using unmanned aerial vehicles have significantly transformed the monitoring of electrical transmission lines by enabling high-resolution, data-driven, and safer assessment approaches. Among these methods, visual inspection using high-resolution cameras remains the most widely adopted due to its simplicity, cost-effectiveness, and ability to capture detailed imagery of transmission components. UAV-mounted optical cameras provide close-range views of conductors, insulators, towers, and fittings, allowing operators to detect visible defects such as cracks, corrosion, loose connections, damaged hardware, and contamination buildup. The ability of rotary-wing UAVs to hover and adjust viewing angles enhances image quality and inspection precision, particularly in complex structures (Nieto-Gomez, 2016, Taylor & Broeders, 2015). Furthermore, advancements in camera resolution and stabilization technologies have improved the clarity of captured images, enabling more accurate fault identification. When integrated

with computer vision and artificial intelligence algorithms, visual inspection data can be automatically processed to detect anomalies, classify defects, and generate inspection reports, thereby reducing human error and improving operational efficiency (Ahmed & Odejebi, 2018, Seyi-Lande, Arowogbadamu & Oziri, 2018).

In addition to visual inspection, infrared thermography has emerged as a critical method for detecting thermal anomalies in transmission systems. UAV-mounted thermal cameras capture infrared radiation emitted by electrical components, allowing for the identification of hotspots that indicate overheating, excessive resistance, or impending equipment failure. This method is particularly valuable for detecting faults that are not visible to the naked eye, such as internal conductor damage, poor electrical connections, or insulation degradation (DeBell, et al., 2015, Deng, et al., 2014). By conducting thermographic inspections under appropriate load conditions, operators can identify areas of abnormal heat generation and prioritize maintenance activities before failures occur. The non-contact nature of infrared thermography enhances safety by allowing inspections to be conducted at a safe distance from energized components. Moreover, the integration of thermal imaging data with analytical tools enables trend analysis and predictive maintenance, supporting more proactive asset management strategies in power systems.

LiDAR technology further enhances UAV-based inspection by providing accurate three-dimensional mapping of transmission corridors. LiDAR sensors emit laser pulses and measure the time taken for the reflected signals to return, generating detailed point cloud data that represent the spatial structure of the environment. This capability is particularly useful for assessing vegetation encroachment, terrain profiling, and clearance distances between conductors and surrounding objects. Accurate 3D models generated from LiDAR data enable utilities to monitor compliance with safety regulations, identify potential risks, and plan vegetation management activities effectively (Jiang, et al., 2017, Zhang, et al., 2017). In addition, LiDAR supports the detection of structural deformations in towers and lines by providing precise geometric measurements. Compared to traditional

surveying methods, UAV-based LiDAR offers faster data acquisition, higher resolution, and improved accessibility in difficult terrains. The integration of LiDAR data with geographic information systems further enhances spatial analysis and decision-making capabilities, enabling comprehensive corridor management (Nwafor, et al., 2018, Seyi-Lande, Arowogbadamu & Oziri, 2018). Figure 4 shows experimental setup for evaluating the effectiveness of motion cueing for UAV control presented by Hing & Oh, 2009.

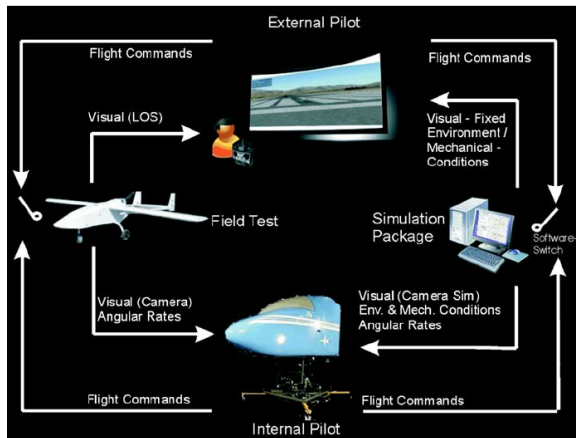


Figure 4: Experimental setup for evaluating the effectiveness of motion cueing for UAV control (Hing & Oh, 2009).

Multispectral and hyperspectral imaging techniques extend the capabilities of UAV inspection by enabling detailed material and environmental analysis. Multispectral sensors capture data across a limited number of spectral bands, while hyperspectral sensors provide a continuous spectrum of wavelengths, allowing for more precise identification of materials and conditions. These imaging techniques are particularly useful for assessing vegetation health, detecting moisture intrusion, and identifying surface degradation on transmission components. For instance, variations in spectral signatures can indicate early stages of corrosion, contamination, or insulation deterioration, which may not be visible through standard optical imaging (Adabo, 2014, Pagnano, Höpf & Teti, 2013). In vegetation management, multispectral imaging enables the assessment of plant health and growth patterns, supporting targeted trimming and maintenance activities. The use of hyperspectral data also facilitates advanced analytics, including classification of materials and detection of

subtle anomalies, thereby enhancing the depth and accuracy of inspection outcomes.

Another important consideration in UAV-based inspection is the distinction between contact-based and non-contact inspection techniques. Non-contact methods, which include visual imaging, thermography, LiDAR, and spectral sensing, dominate UAV applications due to their safety, efficiency, and ability to operate without physical interaction with energized components. These methods allow for rapid data collection over large areas while minimizing risks to equipment and personnel. However, non-contact techniques may sometimes be limited in their ability to assess certain parameters, such as mechanical strength or electrical conductivity, which require direct measurement. In response, emerging contact-based UAV inspection technologies are being developed to address these limitations (Li, et al., 2016, Zhang, et al., 2017). These systems are equipped with specialized tools that enable physical interaction with transmission components, such as sensors for measuring electrical parameters or robotic arms for performing minor maintenance tasks. While contact-based methods offer enhanced diagnostic capabilities, they introduce additional challenges related to UAV stability, control precision, and safety when operating near high-voltage equipment (Nwafor, et al., 2018, Seyi-Lande, Arowogbadamu & Oziri, 2018).

The integration of both contact-based and non-contact inspection techniques provides a comprehensive approach to transmission line monitoring. Non-contact methods serve as the primary means of identifying potential issues across large areas, while contact-based methods can be selectively deployed for detailed assessment and intervention. This combined approach enhances the overall effectiveness of inspection programs by balancing efficiency with diagnostic depth. Furthermore, ongoing advancements in UAV technology, sensor miniaturization, and control systems are expected to improve the feasibility and reliability of contact-based inspections in the future (Jenssen & Rovero, 2018, Zormpas, et al., 2018).

Overall, UAV-based inspection methods represent a significant advancement in the monitoring of electrical transmission infrastructure. By leveraging a combination of visual, thermal, LiDAR, and spectral

sensing techniques, UAVs provide a multi-dimensional understanding of asset conditions, enabling more accurate and timely decision-making. The ability to integrate these methods within a single platform further enhances operational efficiency and reduces the need for multiple inspection systems. As the demand for reliable and resilient power systems continues to grow, the adoption of advanced UAV inspection methods will play a crucial role in supporting modern asset management practices (Gurnell, et al., 2016, Jordan, et al., 2018). Their contribution to improving safety, reducing costs, and enhancing data quality underscores their importance in the ongoing transformation of power infrastructure inspection and maintenance.

2.4. Enabling Technologies and Innovations

Enabling technologies and innovations have played a decisive role in advancing unmanned aerial vehicle applications for electrical transmission line inspection, transforming them from simple data collection tools into intelligent, autonomous, and highly efficient inspection systems. At the core of this transformation is the integration of artificial intelligence and machine learning techniques, which have significantly enhanced the ability to detect, classify, and predict defects in power infrastructure. Machine learning models, particularly deep learning architectures such as convolutional neural networks, are trained on large datasets of labeled images to identify patterns associated with faults including insulator cracks, conductor damage, corrosion, and vegetation interference (Rançon, et al., 2018, Singhal, Bansod & Mathew, 2018). These models enable automated defect detection with high accuracy, reducing reliance on manual interpretation and minimizing human error. In addition, predictive analytics powered by machine learning supports condition-based maintenance by identifying trends and forecasting potential failures before they occur. This shift from reactive to proactive maintenance improves system reliability and reduces operational costs for utility operators.

Closely related to artificial intelligence is the application of computer vision techniques, which provide the foundation for automated image and video analysis in UAV-based inspection systems. Computer vision algorithms process visual data captured by

high-resolution cameras to extract meaningful information about the condition of transmission assets. Techniques such as object detection, image segmentation, feature extraction, and pattern recognition allow for the identification of specific components and anomalies within complex backgrounds. For example, computer vision systems can isolate insulators from surrounding structures and detect surface defects or contamination levels (Mitra, 2017, Russell, et al., 2018). Advanced image processing methods also enable the reconstruction of detailed inspection scenes, improving situational awareness and facilitating more accurate assessments. The combination of computer vision and machine learning creates a powerful analytical framework capable of handling large volumes of inspection data efficiently, thereby accelerating decision-making processes and enhancing the overall effectiveness of UAV-based inspections.

The integration of UAV-generated data with Geographic Information Systems represents another significant innovation in transmission line inspection. GIS platforms serve as centralized systems for storing, managing, analyzing, and visualizing geospatial data collected during UAV missions. By integrating inspection data with spatial information such as terrain models, asset locations, and environmental features, GIS enables a comprehensive understanding of infrastructure conditions within their geographic context. This integration supports advanced applications including asset tracking, risk mapping, vegetation management, and maintenance planning. For instance, GIS can be used to overlay LiDAR-derived point clouds with transmission line data to assess clearance distances and identify potential hazards. Furthermore, GIS platforms facilitate the development of digital twins, which are virtual representations of physical assets that can be continuously updated with real-time data (Ali, et al., 2016, Zhang, et al., 2018). These digital models enable utilities to simulate scenarios, optimize maintenance strategies, and improve long-term asset management. The synergy between UAV data and GIS enhances situational awareness and supports data-driven decision-making in modern power systems.

Autonomous navigation and obstacle avoidance systems are also critical enablers of UAV deployment

in transmission line inspection. These technologies allow UAVs to operate with minimal human intervention while maintaining high levels of safety and efficiency. Autonomous navigation relies on a combination of global navigation satellite systems, inertial measurement units, and onboard sensors to determine the UAV's position and execute predefined flight paths accurately. Advanced algorithms enable dynamic path planning, allowing UAVs to adapt to changing environmental conditions and avoid obstacles such as towers, conductors, and vegetation (Li, et al., 2012, Xu, et al., 2016). Obstacle avoidance systems utilize sensors including LiDAR, ultrasonic sensors, and stereo vision cameras to detect nearby objects and adjust flight trajectories in real time. This capability is particularly important in transmission line inspection, where UAVs must operate in close proximity to complex and potentially hazardous structures. The development of robust autonomous systems reduces the cognitive load on operators, improves mission consistency, and enhances safety by minimizing the risk of collisions and operational errors.

Another key innovation driving the effectiveness of UAV-based inspection systems is the adoption of edge computing and real-time data processing. Traditionally, large volumes of data collected by UAVs were transmitted to centralized servers for processing and analysis, leading to delays in obtaining actionable insights. Edge computing addresses this limitation by enabling data processing directly on the UAV or at nearby edge devices, reducing latency and improving responsiveness (Richardson, et al., 2017). By performing real-time analysis of sensor data, edge computing allows UAVs to identify defects, assess conditions, and make decisions during flight. For example, an onboard system can detect a potential fault and adjust the flight path to capture additional data for further analysis. This capability enhances inspection efficiency by prioritizing critical areas and reducing the need for repeat missions. Additionally, real-time data processing supports immediate reporting and integration with control systems, enabling faster response to identified issues.

The combination of edge computing with artificial intelligence further enhances the autonomy and intelligence of UAV systems. Lightweight machine

learning models can be deployed on edge devices to perform tasks such as image classification and anomaly detection in real time. This reduces the dependency on high-bandwidth communication links and ensures continuous operation even in environments with limited connectivity. Moreover, the integration of edge computing with cloud-based platforms creates a hybrid architecture that balances local processing with centralized analytics, optimizing both performance and scalability. This approach allows utilities to leverage the benefits of real-time insights while maintaining access to comprehensive data analysis and long-term storage capabilities (Saltz & Shamshurin, 2016, Sculley, et al., 2015).

Overall, the convergence of artificial intelligence, computer vision, GIS integration, autonomous navigation, and edge computing represents a paradigm shift in UAV-based transmission line inspection. These enabling technologies not only enhance the accuracy and efficiency of inspections but also support the development of intelligent, adaptive, and scalable monitoring systems. As these innovations continue to evolve, they are expected to further improve the capabilities of UAV systems, enabling more sophisticated analysis, greater autonomy, and deeper integration with smart grid infrastructures (Grover, et al., 2018, Hashem, et al., 2015, Watson, 2017). The ongoing advancement of these technologies underscores their critical role in modernizing power system inspection and ensuring the reliability and sustainability of electrical transmission networks in an increasingly digital and data-driven energy landscape.

2.5. Applications in Transmission Line Inspection

Unmanned aerial vehicles have become indispensable tools in the practical application of electrical transmission line inspection, offering enhanced capabilities for identifying faults, managing risks, and improving the reliability of power infrastructure. One of the most critical applications of UAVs is the detection of structural defects in transmission assets. High-resolution imaging systems mounted on UAVs enable detailed inspection of towers, conductors, insulators, and associated hardware. These systems can identify visible defects such as cracks in structural members, corrosion of metallic components, loose

fittings, and mechanical deformation (Chen, Mao & Liu, 2014, Delen & Demirkan, 2013). Insulators, which are particularly susceptible to contamination, flashover, and mechanical damage, can be closely examined using optical and thermal sensors to detect surface degradation or internal faults. UAVs provide the advantage of accessing hard-to-reach areas and capturing inspection data from multiple angles, thereby improving the accuracy and completeness of structural assessments. When combined with automated image analysis and machine learning techniques, UAVs can rapidly detect and classify defects, enabling timely maintenance interventions and reducing the risk of unexpected failures.

Another significant application of UAVs in transmission line inspection is vegetation monitoring and right-of-way management. Vegetation encroachment is a major cause of power outages, particularly when trees or branches come into contact with transmission lines. UAVs equipped with LiDAR and multispectral sensors can accurately map vegetation growth and assess clearance distances between conductors and surrounding flora. This information allows utilities to identify areas where vegetation poses a risk and prioritize trimming or removal activities (Sharma, Mithas & Kankanhalli, 2014, Van der Aalst, 2016). Compared to traditional ground-based surveys, UAV-based monitoring offers higher resolution data, faster coverage, and improved accessibility in challenging terrains such as forests, mountains, and wetlands. In addition, multispectral imaging enables the assessment of vegetation health, allowing operators to predict growth patterns and implement proactive management strategies. By maintaining safe clearance distances and reducing the likelihood of vegetation-related faults, UAVs contribute to improved system reliability and compliance with regulatory standards.

UAVs also play a vital role in monitoring the environmental impacts on transmission infrastructure. Power lines are exposed to various environmental factors, including extreme weather conditions, temperature fluctuations, pollution, and wildlife interactions, all of which can affect asset performance and longevity. UAV-based inspection systems can monitor these factors by capturing detailed data on environmental conditions and their effects on

infrastructure components. For instance, thermal imaging can reveal overheating caused by environmental stress, while visual and spectral imaging can detect contamination from dust, salt, or industrial pollutants (Côte-Real, Oliveira & Ruivo, 2017, Provost & Fawcett, 2013). In coastal or industrial regions, where corrosion is a significant concern, UAVs can be used to assess the extent of material degradation and support targeted maintenance efforts. Additionally, UAVs can monitor the impact of natural phenomena such as flooding, landslides, and erosion on transmission line stability. This capability enables utilities to understand environmental risks more comprehensively and implement mitigation measures to protect infrastructure and ensure long-term operational integrity.

Predictive maintenance and asset management represent another key application area where UAVs have demonstrated significant value. By providing high-quality, real-time data on asset conditions, UAVs enable utilities to transition from reactive maintenance approaches to predictive and condition-based strategies. Data collected during UAV inspections can be analyzed using advanced analytics and machine learning models to identify patterns and trends indicative of potential failures. For example, repeated detection of minor defects in a specific component may signal the need for preventive replacement before a major failure occurs. Integration of UAV data with asset management systems and geographic information systems allows for comprehensive tracking of infrastructure health over time (Akidau, et al., 2015, Chen, Chiang & Storey, 2012). This facilitates better decision-making regarding maintenance scheduling, resource allocation, and lifecycle management. Predictive maintenance not only reduces operational costs by minimizing unnecessary inspections and repairs but also enhances system reliability by preventing unexpected outages. The ability to prioritize maintenance activities based on actual asset conditions represents a significant advancement in modern power system management.

In addition to routine inspection and maintenance, UAVs are highly effective in emergency response and post-disaster assessment scenarios. Natural disasters such as storms, hurricanes, earthquakes, and wildfires

can cause extensive damage to transmission infrastructure, leading to widespread power outages and significant economic losses. In such situations, rapid assessment of damage is essential for restoring power and ensuring public safety. UAVs can be deployed quickly to survey affected areas, capture real-time imagery, and identify damaged components without exposing personnel to hazardous conditions (Jagdish, et al., 2014, Kelleher & Tierney, 2018, Zaharia, et al., 2016). Their ability to access remote or inaccessible locations makes them particularly valuable in disaster response efforts. UAV-generated data can be used to create detailed maps of affected areas, prioritize repair activities, and coordinate restoration efforts efficiently. Furthermore, UAVs can support ongoing monitoring during recovery operations, ensuring that repairs are carried out effectively and that no additional risks are present.

The use of UAVs in post-disaster assessment also contributes to improved resilience planning. By analyzing data collected after an event, utilities can identify vulnerabilities in their infrastructure and implement measures to strengthen system resilience against future incidents. For example, recurring damage patterns may indicate the need for design improvements, relocation of assets, or enhanced protective measures. UAV-based assessments provide accurate and timely information that supports informed decision-making in both immediate response and long-term planning (Gandomi & Haider, 2015, Inmon, 2005, Kimball & Ross, 2013).

Overall, the diverse applications of UAVs in transmission line inspection demonstrate their transformative impact on power infrastructure management. From detecting structural defects and managing vegetation to monitoring environmental impacts and enabling predictive maintenance, UAVs offer a comprehensive solution for modern inspection challenges. Their role in emergency response and post-disaster assessment further highlights their importance in ensuring the resilience and reliability of electrical transmission systems. As technological advancements continue to enhance UAV capabilities, their applications are expected to expand further, supporting more efficient, accurate, and proactive approaches to infrastructure inspection and

maintenance (Ike, et al., 2018, Kyere Yeboah & Enow, 2018).

2.6. Operational and Technical Challenges

Operational and technical challenges remain significant barriers to the widespread adoption and optimal utilization of unmanned aerial vehicles in electrical transmission line inspection. One of the most prominent limitations is the issue of limited flight endurance, which is largely dictated by battery capacity. Most rotary-wing UAVs, commonly used for detailed inspection tasks, typically have flight times ranging between 20 to 40 minutes, depending on payload and environmental conditions. This constraint restricts the coverage area per mission and necessitates frequent battery replacements or recharging cycles, which can interrupt inspection workflows and increase operational downtime (Uzundu & Ofoedu, 2014). Fixed-wing UAVs offer longer endurance but lack the hovering capability required for close inspection, creating a trade-off between coverage and precision. The addition of advanced sensors such as LiDAR or thermal cameras further increases power consumption, exacerbating the challenge. Although advancements in battery technology, such as lithium-sulfur and hydrogen fuel cells, are being explored, they are not yet widely deployed in commercial UAV systems. Consequently, flight endurance remains a critical bottleneck in large-scale transmission corridor inspection.

Another major challenge lies in data management and processing complexity. UAV-based inspections generate vast amounts of high-resolution data, including images, videos, and point clouds, which require significant storage, processing power, and analytical capabilities. Managing this data efficiently is a complex task, particularly when dealing with large transmission networks that span extensive geographical areas. Data preprocessing steps such as filtering, georeferencing, and stitching are computationally intensive and time-consuming. Furthermore, extracting meaningful insights from raw data requires advanced algorithms and skilled personnel, which may not always be readily available (Efobi, Akinleye & Fasawe, 2017, Ekechi, 2019, Ugwu-Oju, Okeke & Nwankwo, 2018). The integration of multiple data types from different

sensors adds another layer of complexity, as it requires synchronization and compatibility across platforms. Without robust data management frameworks, utilities may struggle to fully leverage the benefits of UAV-based inspection systems, leading to inefficiencies and delayed decision-making.

Environmental factors also pose significant challenges to UAV operations in transmission line inspection. Wind conditions, temperature variations, precipitation, and atmospheric disturbances can all affect flight stability, sensor performance, and data quality. Strong winds can destabilize UAVs, making it difficult to maintain precise positioning, especially during close-range inspections of transmission components. Rain and fog can obscure visibility and degrade the performance of optical and thermal sensors, while extreme temperatures can impact battery efficiency and overall system reliability (Ugwu-Oju, Okeke & Nwankwo, 2018). In addition, electromagnetic interference from high-voltage transmission lines can disrupt UAV navigation and communication systems, leading to potential operational risks. These environmental constraints limit the conditions under which UAVs can be safely and effectively deployed, requiring careful planning and risk assessment prior to each mission.

Communication and signal reliability issues further complicate UAV operations, particularly in remote or challenging terrains where transmission lines are often located. UAVs rely on stable communication links for command and control, as well as for real-time data transmission. These links can be affected by obstacles, distance, and interference, resulting in signal degradation or loss. In such cases, the UAV may lose connectivity with the ground control station, posing risks to both the equipment and the surrounding infrastructure. Although fail-safe mechanisms such as return-to-home functions are commonly implemented, they may not always be sufficient in complex environments (Uzundu & Ofoedu, 2011, Yeboah & Enow, 2018). The use of cellular networks and satellite communication can extend operational range, but these solutions introduce additional costs and may still be subject to latency or coverage limitations. Ensuring reliable communication remains a critical requirement for safe and efficient UAV-based inspection.

Cybersecurity and data privacy concerns represent another important dimension of operational challenges. UAV systems are increasingly connected to digital networks, making them vulnerable to cyber threats such as hacking, data interception, and unauthorized access. Sensitive infrastructure data collected during inspections, including detailed images and geospatial information, could be exploited if not properly secured. Cyberattacks on UAV systems could also compromise flight control, leading to potential safety hazards and operational disruptions (Onovo, Gado & Atobatele, 2012, Ugwu-Oju, Okeke & Nwankwo, 2018). Protecting UAV systems requires the implementation of robust cybersecurity measures, including encryption, secure communication protocols, and access control mechanisms. In addition, compliance with data protection regulations is essential to ensure that collected data is handled responsibly and ethically. Utilities must invest in cybersecurity infrastructure and develop policies to mitigate risks associated with digital vulnerabilities.

The interplay of these operational and technical challenges highlights the complexity of deploying UAV systems in real-world transmission line inspection scenarios. While UAVs offer significant advantages over traditional inspection methods, their effectiveness is contingent upon addressing these limitations through technological innovation, strategic planning, and regulatory support. For instance, improvements in battery technology and energy management systems could extend flight endurance, while advancements in data analytics and cloud computing could streamline data processing and management (Ugwu-Oju, Okeke & Nwankwo, 2018). Enhanced sensor technologies and robust navigation systems could mitigate environmental impacts, and the development of resilient communication networks could improve signal reliability. Similarly, the adoption of comprehensive cybersecurity frameworks would safeguard sensitive data and ensure system integrity.

In conclusion, operational and technical challenges remain critical considerations in the implementation of UAV-based transmission line inspection systems. Addressing these challenges requires a multidisciplinary approach that combines engineering innovation, data science, regulatory compliance, and

operational expertise. As research and development efforts continue to advance UAV technologies, it is expected that many of these limitations will be progressively mitigated, paving the way for more efficient, reliable, and secure inspection practices. Ultimately, overcoming these challenges is essential for unlocking the full potential of UAVs in modernizing power infrastructure inspection and supporting the transition toward more resilient and intelligent energy systems.

2.7. Regulatory, Economic, and Implementation Issues

Regulatory, economic, and implementation issues play a critical role in shaping the adoption and effectiveness of unmanned aerial vehicles in electrical transmission line inspection. One of the foremost considerations is compliance with airspace regulations, which govern the operation of UAVs to ensure safety and coordination with other airspace users. Regulatory frameworks typically impose restrictions on flight altitude, operational range, line-of-sight requirements, and proximity to populated areas or critical infrastructure. In many jurisdictions, operators must obtain licenses, certifications, and flight permits before conducting UAV missions. These requirements, while necessary for safety, can introduce administrative complexity and delay deployment, particularly for routine inspection activities that require frequent flights. Additionally, cross-border infrastructure projects may face varying regulatory standards, complicating multinational operations (Yetunde, Onyelucheya & Dako, 2018). The evolving nature of UAV regulations means that operators must continuously adapt to new policies, which can create uncertainty and hinder long-term planning. Achieving a balance between regulatory control and operational flexibility remains a key challenge for policymakers and industry stakeholders.

From an economic perspective, the adoption of UAV technology necessitates a careful evaluation of costs and benefits compared to traditional inspection methods. UAV systems require initial capital investment in platforms, sensors, software, and training, which can be substantial depending on the scale and sophistication of the system. However, when compared to conventional approaches such as

helicopter-based inspections or manual ground surveys, UAVs offer significant cost savings over time (Aye and Tawose, 2015). Reduced labor requirements, lower fuel consumption, and faster data acquisition contribute to improved operational efficiency and lower recurring expenses. Furthermore, the ability of UAVs to enable predictive maintenance reduces the likelihood of costly equipment failures and unplanned outages, thereby enhancing return on investment. Despite these advantages, the economic viability of UAV adoption depends on factors such as the size of the transmission network, frequency of inspections, and availability of skilled personnel. Small utilities or organizations with limited budgets may find it challenging to justify the initial investment, even if long-term benefits are evident.

The successful implementation of UAV-based inspection systems also depends on the availability of a skilled workforce capable of operating and maintaining these technologies. UAV operations require expertise in flight control, mission planning, data acquisition, and safety protocols, as well as proficiency in data analysis and interpretation. In addition, personnel must be trained to handle advanced technologies such as artificial intelligence, geospatial analysis, and remote sensing. The interdisciplinary nature of UAV applications means that operators must possess a combination of engineering, information technology, and domain-specific knowledge related to power systems (Aye and Tawose, 2016, Lawal & Oduleye, 2018). Training programs and certification processes are essential to ensure that personnel meet regulatory requirements and maintain high standards of operational safety. However, the rapid pace of technological advancement creates a continuous need for upskilling and professional development, which can place additional demands on organizations. In regions where access to training resources is limited, the shortage of qualified personnel can become a significant barrier to adoption.

Standardization and interoperability present further challenges in the deployment of UAV systems for transmission line inspection. The diversity of UAV platforms, sensor types, and software solutions can lead to compatibility issues and fragmented workflows. Without standardized data formats and

communication protocols, integrating data from different systems can be difficult and time-consuming. This lack of interoperability can hinder collaboration between organizations, limit the scalability of UAV operations, and reduce the overall efficiency of inspection processes (Lawal & Oduleye, 2018, Okonkwo, Ogunwole & Okeke, 2018). Standardization is particularly important for ensuring consistency in data quality, enabling benchmarking, and facilitating the integration of UAV data with existing asset management and geographic information systems. Industry-wide standards and best practices are still evolving, and their development requires collaboration among manufacturers, service providers, regulators, and utility companies. Establishing common frameworks for data exchange and system integration is essential for maximizing the benefits of UAV technology.

Barriers to large-scale adoption are especially pronounced in developing economies, where financial, institutional, and infrastructural constraints may limit the deployment of advanced technologies. High upfront costs, limited access to financing, and competing priorities in infrastructure development can make it difficult for utilities in these regions to invest in UAV systems. In addition, regulatory frameworks may be underdeveloped or inconsistently enforced, creating uncertainty and potential risks for operators. Limited access to reliable communication networks and data processing infrastructure can further constrain the effectiveness of UAV-based inspection systems (Olude & Badmus, 2015, Kolndadacha, et al., 2013). Workforce challenges are also more acute in developing economies, where there may be a shortage of trained professionals and limited opportunities for capacity building. Cultural and organizational resistance to new technologies can also impede adoption, particularly in environments where traditional methods are deeply entrenched.

Despite these challenges, there are opportunities to overcome barriers and promote the adoption of UAV technology in transmission line inspection. Collaborative partnerships between governments, industry, and academic institutions can support the development of regulatory frameworks, training programs, and research initiatives. Financial incentives, such as subsidies or public-private

partnerships, can help offset initial investment costs and encourage adoption among smaller utilities. The use of scalable and modular UAV systems can also reduce costs and allow organizations to gradually expand their capabilities (Okonkwo, Ogunwole & Okeke, 2018, Olamide & Badmus, 2018). In addition, cloud-based platforms and open-source software solutions can improve accessibility and reduce the need for extensive infrastructure investment. International cooperation and knowledge sharing can further support the transfer of best practices and technologies to developing regions.

Overall, regulatory, economic, and implementation issues are central to the successful integration of UAVs into transmission line inspection practices. While these challenges are significant, they are not insurmountable, and ongoing advancements in technology, policy, and capacity building are expected to address many of these limitations. By aligning regulatory frameworks with technological innovation, optimizing economic strategies, and investing in workforce development, stakeholders can create an enabling environment for UAV adoption. This will not only enhance the efficiency and reliability of transmission line inspection but also contribute to the broader modernization of power infrastructure systems in both developed and developing economies (Mabo, Swar & Aghili, 2018).

2.8. Future Directions and Conclusion

The future of unmanned aerial vehicle applications in electrical transmission line inspection is being shaped by rapid technological advancements and the growing demand for intelligent, resilient, and data-driven power systems. Emerging trends such as swarm UAVs, digital twins, and 5G-enabled platforms are expected to redefine how inspection and monitoring activities are conducted. Swarm UAV technology involves the coordinated deployment of multiple drones operating collaboratively to cover extensive transmission corridors simultaneously. This approach significantly improves inspection speed, redundancy, and efficiency, particularly for large-scale networks. Digital twin technology further enhances this capability by creating dynamic, real-time virtual representations of transmission infrastructure, continuously updated with UAV-acquired data. These

digital models enable predictive simulations, scenario analysis, and optimized maintenance planning, thereby supporting proactive asset management. The integration of 5G communication networks provides high-speed, low-latency connectivity, enabling real-time data transmission, remote control, and seamless coordination among UAV systems, even in complex and geographically dispersed environments.

Advancements in battery technology and energy efficiency are also expected to play a crucial role in overcoming one of the most persistent limitations of UAV systems, namely limited flight endurance. Research into next-generation energy storage solutions, including solid-state batteries, lithium-sulfur systems, and hydrogen fuel cells, holds the potential to significantly extend flight durations and enhance payload capacity. Improvements in energy management systems, lightweight materials, and aerodynamic design are further contributing to increased operational efficiency. These developments will enable UAVs to conduct longer missions with fewer interruptions, making them more suitable for large-scale transmission line inspections and reducing operational costs associated with frequent battery replacement or recharging.

The integration of UAV systems with smart grid and Internet of Things ecosystems represents another important direction for future development. As power systems become increasingly digitized, the ability to collect, analyze, and act on real-time data is essential for maintaining system reliability and efficiency. UAVs can serve as mobile data acquisition platforms within these ecosystems, providing high-resolution, localized information that complements data from fixed sensors and monitoring devices. When integrated with IoT-enabled infrastructure, UAVs can support continuous monitoring, automated fault detection, and real-time decision-making. This convergence of technologies facilitates the development of intelligent energy systems capable of self-diagnosis, adaptive response, and optimized performance. Moreover, the incorporation of artificial intelligence into these integrated systems will further enhance automation, enabling UAVs to operate with minimal human intervention and to make context-aware decisions during inspection missions.

To fully realize the potential of UAV-based inspection systems, policy frameworks and regulatory strategies must evolve in tandem with technological advancements. Policymakers are encouraged to develop flexible and adaptive regulations that support innovation while ensuring safety and security. This includes the establishment of standardized operational guidelines, streamlined approval processes, and clear protocols for data management and cybersecurity. Investment in research and development is also essential to address existing technical challenges and explore new applications. Collaborative efforts among governments, academic institutions, and industry stakeholders can accelerate innovation and facilitate the development of best practices. In addition, capacity-building initiatives and training programs are needed to equip the workforce with the skills required to operate and manage advanced UAV systems effectively.

Future research opportunities are abundant and span multiple disciplines, including engineering, data science, and policy studies. Areas of particular interest include the development of more robust autonomous navigation systems, enhanced sensor technologies, and advanced data analytics methods. Research into the integration of UAVs with renewable energy systems and decentralized grids could further expand their applications in modern power networks. Additionally, studies on the economic and environmental impacts of UAV adoption can provide valuable insights for decision-makers and support the development of sustainable implementation strategies.

In summary, UAV technology has demonstrated significant potential in transforming electrical transmission line inspection by improving safety, efficiency, and data quality. The review has highlighted the evolution of inspection methods, the role of enabling technologies, and the diverse applications of UAV systems in power infrastructure management. It has also identified key operational, technical, regulatory, and economic challenges that must be addressed to achieve widespread adoption. Looking ahead, the continued advancement of UAV technologies, coupled with supportive policy frameworks and collaborative research efforts, will drive the development of more intelligent, autonomous, and integrated inspection systems.

Ultimately, UAVs are poised to play a central role in the modernization of power infrastructure, contributing to more reliable, resilient, and sustainable energy systems worldwide.

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