Applying AI to Power Line Inspection: Recent Developments

Gokhan Erdemir[1,*], Aydin Tarik Zengin[2], Tahir Cetin Akinci[2, 3]

[1] University of Tennessee at Chattanooga, Dep. of Eng. Management & Technology, Chattanooga, TN, USA.
[2] Istanbul Technical University, Dep. of Electrical Engineering, Istanbul, Turkiye.
[3] University of California Riverside, WCGEC, Riverside, CA, USA.

* Corresponding author. Tel.: +1-423-425-5840; email: gokhan-erdemir@utc.edu (G.E.)
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Abstract: As the backbone of modern civilization, electricity fuels countless homes, businesses, and industries worldwide. However, this indispensable resource's safety, reliability, and efficiency hinge upon the regular maintenance and inspection of electric power lines. With the rise of AI technologies, there has been mounting interest in their application to power line inspection, with the overarching goal of augmenting the accuracy and efficiency of this process. This exhaustive review article surveys the latest research in the field of AI for power line inspection, with a specific emphasis on automated image recognition, predictive maintenance, robotic inspection, data analytics, and automated reporting. Through a meticulous literature analysis, we expose AI technologies' potential advantages and drawbacks in power line inspection and highlight the key challenges and opportunities for future research. Our sweeping review emphasizes the unprecedented potential of AI technologies in fundamentally transforming power line inspection with an array of inventive and pioneering approaches to enhancing the safety and reliability of this vital infrastructure.

Keywords: Power line inspection, artificial intelligence, machine learning, predictive maintenance, robotic inspection, data analytics, image recognition, automated reporting

1. Introduction

Electricity is an indispensable resource for modern society as it powers our homes, workplaces, and industries [1–3]. However, electricity generation, transmission, and distribution pose unique challenges, especially concerning the electrical grid's safety and reliability, comprising a vast network of power lines, transformers, and other equipment [4]. Power line inspection plays a crucial role in addressing these challenges by helping to identify potential problems before they escalate [5].

Power line inspection involves visually inspecting power lines, transformers, and other equipment and testing various components for potential problems [6, 7]. The primary objective of this inspection is to identify defects, damage, or wear that could cause power outages or other issues. Inspection is especially vital for overhead power lines exposed to the elements and can be damaged by storms, winds, and other natural factors. Underground power lines are also inspected to ensure proper laying and not affected by ground movements or other factors [6, 8]. The importance of power line inspection cannot be overstated, as power outages can be costly for businesses and individuals and have severe consequences for public safety [9]. In addition, power outages can disrupt critical infrastructure such as hospitals, water treatment plants, and transportation systems [10]. However, despite the significance of power line inspection, several challenges remain. One of the main challenges is the enormous size of the electrical grid, with over 640,000 miles of high-voltage transmission lines and millions of miles of distribution lines in the United States alone. Manual inspection of this vast infrastructure network is difficult and expensive, meaning that some potential problems may be noticed once they become more serious [11, 12]. Another challenge is the hazardous nature of power line inspection, with inspectors regularly exposed to high-voltage electricity, dangerous heights, and other risks. This exposure can lead to injury or even death, making it essential to find ways to minimize these risks.

To overcome these challenges, there is a growing interest in using artificial intelligence (AI) technologies for power line inspection. AI technologies, such as image processing and machine learning, can help automate the inspection process, making it faster, safer, and more accurate. In this review, we will explore the use of AI technologies in power line inspection and examine some of the associated benefits and challenges.

2. Automated Image Recognition in Power Line Inspection

Artificial intelligence (AI) and computer vision use in power line inspection have been a rapidly growing area of research in recent years, as the potential benefits of these technologies for power line inspection are numerous. Automated defect detection using image recognition is gaining popularity in this field. By analyzing images of power lines, transformers, and other equipment for potential defects, AI algorithms can identify issues such as cracks or corrosion, allowing maintenance crews to take action before more severe problems arise [13–15].

However, one of the main challenges associated with using AI in power line inspection is ensuring the accuracy and reliability of AI algorithms. These algorithms must be carefully designed and tested to ensure that they can accurately identify potential defects without generating false positives or missing real defects. Recent research has been focused on developing more advanced algorithms that can identify more subtle defects and distinguish them from benign anomalies in the data [15, 16].

Another technique that has shown promise in power line inspection is deep learning algorithms. These algorithms can be trained on large images and other data datasets to identify potential defects accurately. For example, deep learning algorithms can be trained to detect changes in the size or shape of power line components, indicating wear or damage that could lead to power outages. By using deep learning techniques, inspectors can quickly identify potential issues and prioritize repairs based on the severity of the defects [17, 18]. In addition to these techniques, unmanned aerial vehicles (UAVs) are also used for automated image recognition in power line inspection. UAVs equipped with high-resolution cameras can capture images of power lines and other equipment from various angles, allowing inspectors to detect defects that might not be visible from the ground. By using UAVs, power companies can also reduce the need for manual inspections, which can be time-consuming and expensive [19, 20]. However, using UAVs for power line inspection also presented challenges. Safety is a major concern, and UAVs must comply with relevant regulations and safety guidelines. Power companies must coordinate with regulatory agencies to ensure that their use of UAVs is safe and legal. Additionally, the data collected from UAVs must be carefully analyzed and interpreted, which requires specialized knowledge and skills [21, 22].

Despite these challenges, using AI and computer vision in power line inspection can significantly improve power line maintenance efficiency, accuracy, and safety. As technology advances, we will likely see even more innovative solutions to the challenges facing power line inspection in the future. For example, the development of new sensors and data analysis techniques could further improve the accuracy and reliability of automated defect detection. At the same time, advances in robotics and automation could reduce the need for human inspectors altogether. Continued collaboration between researchers, power companies, and regulatory agencies will be necessary to achieve these goals.

3. Predictive Maintenance in Power Line Inspection

Predictive maintenance (PM) is a maintenance plan that determines when maintenance is required to avoid equipment failure using data analysis and machine learning techniques. Real-time equipment performance monitoring and data analysis techniques are used to forecast when maintenance is necessary before a failure. As maintenance is only carried out when necessary, minimizing downtime and repair expenses, this strategy enables more efficient and economical maintenance.

Kawada *et al*. developed high-precision online operation/maintenance systems to monitor and diagnose the condition of substation equipment, detect signs of abnormalities or end-of-life, and predict them with high accuracy [23]. These systems are necessary because substation power delivery apparatus tends to operate without long-term shutdown for overhaul inspection and maintenance. Predictive maintenance can prevent and avoid power problems in electrical distribution systems using monitoring instruments and powerful software tools. Full disclosure power monitoring instruments capture comprehensive information on power disturbances, harmonics, flicker, and power consumption [24]. Azam *et al*. propose condition-based predictive maintenance for high reliability/availability-oriented industries, using monitored power-quality data and classification techniques to evaluate the health indices of components [25]. Trending techniques and neural networks can be used to predict failures before they manifest. Stillman *et al*. presented repairable system and life data methods for assessing preventive maintenance of power distribution systems [26]. It proposed that power lines can be treated as systems that are minimally repaired upon failure and restored to a "bad as old state" by preventive maintenance. The paper focuses on an urban feeder study to determine underlying trends and whether a Poisson process can characterize interruptions [26].

NOVA is a framework developed by Wu *et al*. to assess the effectiveness of machine learning and data mining algorithms for preventive maintenance on the electrical grid [27]. The framework comprises three stages: evaluating the quality of input data, assessing the results of machine learning and data mining, and evaluating the improvement in reliability. Meanwhile, Da Silva *et al*. introduced a novel methodology for real-time monitoring of the insulation conditions of power transmission lines, enabling the detection and locating anomalies during operation and facilitating preventive maintenance [28]. The method uses harmonic decomposition of the leakage current and a neural network to find faults. Experimental measurements were obtained to validate the results. Pagnano *et al*. discuss the current state of automated power line inspection using robots, which can be dangerous, expensive, and unreliable [29]. They propose a roadmap for implementing a "Fully Automated Live Line Power Line Inspection Concept" with an autonomous mobile platform and a power line data management system. On the other hand, Online Monitoring (OLM) technologies and new diagnostic and prognostic methods are used to anticipate, identify, and resolve equipment and process problems, reducing generation costs while ensuring plant safety, efficiency, and immunity to accidents [30]. Toit proposed a low-complexity anomaly detection algorithm that enables predictive maintenance in the electricity distribution sector by projecting multivariate Gaussian functions onto pre-selected substation data points [31]. Results demonstrate early positive detection of anomalous load behavior. Raza and Ulansky presented a study that models predictive maintenance, proposing decision rules and mathematical models to calculate maintenance indicators for an arbitrary distribution of time to failure, and illustrates the advantage of PM over corrective maintenance through a numerical example [32]. Sisman and Mihai discuss analyzing acquired data to achieve predictive maintenance of power supply equipment used in telecommunication systems [33]. In comparison, Carchiolo *et al*. proposed an NLP-based analysis of failure reports in power plants to reduce unplanned downtime and repair time while increasing operational efficiency and reducing costs [34]. Alvares and Gudwin propose an integrated system for predictive maintenance and operation of electrical generation assets at the Coaracy Nunes hydropower plant, using the OSA-CBM model and fuzzy production rules [35].

To enhance the safety and reliability of power line inspection, Fang *et al*. presented a framework that utilizes unmanned aerial vehicles (UAVs) to detect power pylons [36]. The framework employs multi-source information, including camera calibration, power pylon model projection, clustering, and feature extraction and matching to select images that potentially contain faulty power pylons automatically. Meanwhile, Velasquez and Flores highlighted the potential of artificial intelligence and machine learning in improving current maintenance techniques for hydropower plants by facilitating condition monitoring, fault diagnosis, and predictive maintenance [37]. Concerning power lines, predictive maintenance is crucial. For the reliable delivery of electricity, it is necessary to maintain power lines, an essential infrastructure. Serious repercussions, such as lost productivity, revenue, and public safety, can result from equipment failure and power outages. Utility companies can prioritize maintenance on critical components and reduce unnecessary maintenance on less critical components by using predictive maintenance to optimize their maintenance schedules and resource allocation. This may lead to reduced costs and increased effectiveness. In conclusion, predictive maintenance is an essential tool for preserving the dependability and safety of power lines and can assist utilities in lowering costs, minimizing downtime, and enhancing system performance.

4. Robotic Inspection in Power Line Inspection

Power line robotic inspection is the automated use of mobile robots to inspect power transmission line equipment instead of manually inspecting equipment, which entails sending human operators to the tops of buildings. Using a ground wire and an arc-shaped arm to navigate obstacles created by auxiliary equipment and pass around transmission towers, the robot is intended to navigate overhead power transmission lines unattended.

The inspection robots have several sensors, cameras, and other measurement tools that enable them to find flaws or anomalies in the equipment it examines. The control center analyzes and uses the robot's data to identify potential problems before they become serious.

A mobile robot has been developed by Sawada *et al.* to automate the inspection of power transmission line equipment by navigating overhead power transmission lines unattended, using a ground wire and an arc-shaped arm to maneuver over obstructions created by subsidiary equipment on the ground wire such as weights, and passing around transmission towers by unfolding the arm and attaching it to the ground wire on opposite sides of the tower [38]. One of the first uses of the idea proposed by Sawada is applied to an autonomous robot in the power line inspection and proposed by Peungsungwal *et al*. [39].

Using unmanned aerial vehicles (UAVs) equipped with video surveillance equipment to perform power line inspections is a possible solution to the labor-intensive and expensive procedures involved in the process. Jones *et al*. presented a dynamic model for a ducted-fan rotorcraft which can be controlled by visually tracking the overhead supply lines to determine and regulate the position of the simulated vehicle relative to the lines [40]. Another approach is a robot with three serial arms that can move on electric power lines and execute monitoring tasks. Tavares *et al*. presented such a robot for infrastructure inspection, forest fire surveillance, and wildlife study, with the third arm providing stability and assisting in overtaking obstacles and maintaining torques. In contrast, the two other arms provide motion, and two vertical rotation joints allow the robot to perform curves and control its center of mass [41].

Katrasnik *et al*. discussed the importance of power line inspection and proposed a new concept that combines both climbing and flying principles to improve the quality and safety of inspections [42]. Montambault and Pouliot proposed a compact mobile teleoperated robot that can inspect and maintain power lines, including working on live lines up to 735 kV and 1,000 A, with a robust design[43]. The same authors presented a new study showing a new robot performing basic maintenance tasks on power lines, including programmable pan-and-tilt camera (PPTC) units and a dual-end effector robotic arm designed for work on bundled conductors, along with implemented application modules [43]. A similar robot is presented by Jian *et al*. which was designed as a cable car with two multi-joint arms for power transmission line inspection and maintenance, with two locomotion modes for navigating on the line and obstacle-surmounting capabilities [44]. Oliveira and Lages proposed a method for automatically detecting faults in transmission lines using thermographic images, which are intended to be embedded in a robot and allow for extended and safer inspections; experimental results demonstrate its effectiveness [45]. Katrasnik *et al*. proposed their climbing and flying robot as a book chapter [46]. They showed their abilities, such as position control, automatic power line tracking, obstacle avoidance, communication, image acquisition, and automatic fault detection [46].

Wang *et al*. have presented their new inspection robot called SmartCopter, which is based on an Unmanned Autonomous Helicopter (UAH). The robot is designed to inspect transmission lines and is the successor of their previous study [47]. Its primary objective is to reduce the risks associated with manual and helicopter inspections [48]. Finotto *et al*. proposed a flexible and portable robotic manipulator made of insulated material designed to increase the safety and efficiency of inspecting overhead distribution power lines from the ground level [49]. Lages and Scheeren presented an embedded module that can automate thermographic inspection by capturing video streams from infrared and visible image cameras. The module processes the images to detect faults and sends the results to a supervision station through a synthetic image stream [50]. Pagnanot *et al*. has presented state-of-the-art VTOL unmanned aerial vehicles (UAVs) and rolling-on-wires robots (RWR) to create a roadmap for a fully automated live line power line inspection concept [29]. Luque-Vega *et al*. proposed an unmanned aerial system that utilizes a quadrotor helicopter for high-voltage power line inspection. The focus is on equipping the system with the necessary payload for qualitative inspection [51].

Similarly, Chang *et al*. introduced a hybrid power line inspection robot that can land on the overhead ground wire, climb, take off, and fly over obstacles. The robot's outdoor experimental results demonstrate its effectiveness and low power consumption [52]. Miller *et al*. presented a compact robotic device for power line inspection and cleaning that uses V-grooved wheels to grip the line. It also has a video camera and scrub brush for inspection and cleaning [53]. Zengin *et al*. presented a low-cost mobile robot that can move on electrical transmission lines to inspect them continuously, gather uninterrupted data from sensors and cameras, and identify potential problems in advance to avoid high risks and minimize losses in case of possible breakage [54]. Their successive study presented a new approach to measuring the sag amount in power lines using sensor data from a power line inspection robot, allowing for precise and reliable measurements with an error rate of less than 2 percent [55]. Zengin proposed a power-line temperature mapping method using the robot in their previous study and showed an accurate map [56]. Robotic power line inspection is crucial because it offers a safer, more effective, and economical means of identifying and diagnosing issues with power transmission lines. It eliminates the dangers associated with manual inspections and makes it possible to monitor power lines continuously, helping to prevent outages and guarantee an uninterrupted electricity supply.

With the development of technologies like sensors, AI, and machine learning, it is anticipated that robotic inspection of power lines will become more widespread and sophisticated in the future. Robots can collect and analyze more data, improving problem prediction, maintenance planning, and decision-making.

Additionally, robotic inspection will become more autonomous, requiring less human involvement, and allowing for instantaneous decision-making, making it more effective and reliable.

5. Data Analytics in Power Line Inspection

Using data analytics tools to analyze power transmission lines has become increasingly popular in recent years [57–59]. Gathering accurate continuous information from the power lines is crucial for data analysis and predicting possible problems. Traditional inspection ways, such as foot patrol and helicopter-assisted methods, are potentially dangerous under occupational health and safety, have high operational costs, and take a long time for investigation and maintenance [7]. And also, it is unsustainable to gather data continuously from the power lines in traditional ways. It would be a more effective way to use advanced technologies to ensure sustainability. Unmanned aerial vehicles (UAVs) have provided a more efficient and automated method for transmission line inspection [57, 60, 61]. UAVs can provide sustainable, low-cost, and accurate data for overview inspection of transmission lines and effectively inspect power lines [61]. Moreover, power line inspection robots have the advantages such as low-cost inspections and maintenance, close-range inspection, work safety, gathering reliable data from lines, online monitoring, easy operation, etc. [60, 62]. These robots can avoid temporary power supply interruptions affecting the end user and transmission grid, reduce maintenance costs and hazards, and provide accurate data for maintenance [60], [62]. In literature, most research has tackled three primary obstacles to using deep learning for power line inspection based on the vision to make implementing the system easier. These include (i) insufficient training data, (ii) class imbalance or imbalance dataset, and (iii) identifying small components and faults [57].

Additionally, integrating global positioning systems, geographic information systems, computer network communication technology, and other technologies can help design an intelligent inspection system for transmission lines [59]. Furthermore, multi-robot cyber-physical systems can effectively monitor and maintain transmission lines. And also, these kinds of systems can provide accurate, reliable, and sustainable data for analysis and forecasting tools [63]. Data analytics, cyber-physical systems, power line inspection robots, and other advanced technologies can significantly improve power transmission line monitoring, inspection, and maintenance processes. These technologies can provide continuous, sustainable, and accurate data to analysis tools. Thus, it will be more effective to use data analysis in powerline inspections. These technologies can provide more efficient, automated, and accurate methods for transmission line inspection, reduce maintenance costs and hazards, increase worker safety, and ensure the safe and reliable operation of the power grid.

The use of data analytics can significantly improve inspection and maintenance activities for power transmission lines [60]. Traditional inspection methods, which need working at heights of tens of meters above the ground and close to live lines carrying thousands of volts, may be time-consuming, highly hazardous for inspection technicians, less efficient, and unsustainable [64]. However, the development of cyber-physical systems such as UAVs has provided a sustainable and reliable method for power transmission line inspection [51, 60, 65]. Moreover, cyber-physical systems for transmission line inspection have the advantages of low operational cost, high safety, sustainability, high reliability, satisfactory close-range inspection, and easy operation [66]. These robots can avoid temporary power supply interruptions affecting the end user and transmission grid, reduce maintenance costs and hazards, and provide accurate and robust data for transmission line maintenance [66, 67]. Using deep learning for vision-based inspection of power lines such as YOLOv5s is an effective way to improve the accuracy of detecting various critical components, faults, and obstacles in transmission [51]. Additionally, integrating global positioning systems, geographic information systems, wireless sensor networks, and other technologies may help design an intelligent inspection system for transmission lines [68]. Furthermore, multi-robot cyber-physical systems based on inspection robots, wireless sensor networks, and multi-agent theory can effectively monitor and maintain transmission lines [69]. In conclusion, using data analytics, UAVs, transmission line inspection robots, and other advanced technologies can significantly improve inspection and maintenance activities for power transmission lines. These technologies can provide more efficient, automated, and accurate methods for transmission line inspection, reduce maintenance costs and hazards, and ensure the safe and reliable operation of the power grid.

Using various research results, machine-learning models can be developed to identify defects and predict maintenance needs for power transmission lines. Chen *et al*. emphasized accurately predicting icing loads on transmission lines for power-grid safety and stability. Still, they noted that machine-learning models need more prediction precision, randomness in selecting kernel functions and model parameters, and general applicability [70]. Mobile robots can improve the efficiency and safety of monitoring, inspection, and maintenance tasks along transmission lines [71]. They state that mobile robots can improve efficiency, reduce labor costs, increase sustainability, and reduce the risk of worker injury [71]. Image recognition and machine learning can identify composite insulators and detect power transmission line edges [72, 73]. Deep learning and big data-based fast image recognition technology have been applied to identify transmission towers [74]. Researchers proposed a method that uses fast image recognition technology based on big data to identify transmission towers [74]. Machine learning methods can also predict potential fault events in the smart power grid [75].

Anomaly detection in power transmission lines, such as overheating, over noise, obstacle, and icing loads detection, is critical for ensuring safe and reliable operation. Various intelligent analysis techniques have been proposed for anomaly detection. For instance, LIDAR mounted on UAVs can measure the distance between power lines and surrounding objects to detect clearance anomalies [76]. Automatic visual shape clustering can be used for pin-missing transmission line defects [77]. Hybrid frameworks based on three-phase current and voltage waveforms measured during fault events can detect, classify, diagnose, and map power transmission lines [13]. Real-time detection and classification of faults can also be achieved using a phasor measurement unit [14]. Therefore, intelligent data analysis techniques have been proposed for anomaly detection in power transmission lines.

6. Automated Reporting in Power Line Inspection

Automated reporting in power line inspection has been an area of research in recent years [7, 51, 57, 58, 60, 61, 78]. The traditional inspection ways of transmission lines are slow, expensive, and potentially dangerous [7]. It is not possible to perform simultaneous reporting of errors and problems promptly. Therefore, fast detection and data transfer systems should be used. The use of UAVs has been proposed as a solution to this problem [7, 51, 57, 58, 60, 61, 78]. UAVs can be used for power line inspection, and they are faster than traditional inspection ways or even better accuracy than costly helicopter inspection [51, 60].

Another advantage of using UAVs for inspection is fast and accurate data transfer and instant reporting. Vision-based inspection systems generally use deep learning techniques to detect and recognize possible faults. It is possible to obtain accurate and robust feedback from power transmission lines with this approach. Thus, it is possible to effectively gather the accurate and balanced training data needed by deep learning. Multi-modal sensor systems and object detection have also been proposed for automated inspection tasks [78]. The inspection of vegetation undercuts of power line corridors has been automated using UAVs and photogrammetric computer vision systems [79]. The use of target detection technology based on embedded devices and convolutional neural networks has been proposed for power patrol [63]. As a result, using UAVs and deep learning-based automated inspection systems can improve the efficiency and accuracy of power line inspection and support sufficient sources and data for reporting.

Recent research has focused on using deep learning and image recognition technologies for automated reporting in power line inspection. These technologies have been used to develop autonomous vision-based power line inspection systems using cyber-physical systems like UAVs and mobile robots. The main challenge in this area is the need for training data and detecting small components and foreign objects. Researchers have proposed AI-based methods to detect obstacles and unwanted objects in power transmission line inspection. Additionally, machine learning algorithms and image processing techniques can be combined to generate automated reports that provide detailed information about the condition of power lines. Developing software tools for generating automated reports in power line inspection is possible using these techniques. UAVs equipped with remote sensing technologies can be carriers to undertake accurate power line inspections. Developing autonomous UAV inspection systems is essential in reducing costs and improving the efficiency of power line inspections.

Using UAV images for the automatic inspection of power lines allows for the acquisition of the power lines' spatial position and real-time detection of transmission line components. Additionally, this method can generate an actual map of defects on power transmission lines. A teleoperated intelligent controller vehicle sonar tracking checker, designed using a UAV to collect data on power lines for preventive maintenance of high-voltage lines, has been developed to reduce inspection costs and minimize the risk of human injury. The efficiency of power line inspections can be enhanced by implementing a task unloading strategy for multi-UAVs based on deep reinforcement learning.

7. Conclusion

This study highlights the potential advantages and drawbacks of using AI technologies in power line inspection with a thorough literature review. The research mainly focused on five parts. These are the use of (a)AI and computer vision; (b) predictive maintenance; (c) robotics; (d) data analytics; and (e) automated reporting; in power line inspection. Overview, developments, and applications of recent research on these five topics were presented in detail. Our literature review focuses on the potential of AI technologies and their applications in power line inspection through innovative and pioneering approaches to improving the safety and reliability of this critical infrastructure. With the emergence of AI technologies, there is growing interest in their application to power line inspection to enhance the accuracy and efficiency of the process. AI applications will produce striking results in this area, significantly increasing efficiency. However, data collection and robotic maintenance/repair are still very challenging in these lines with high voltage and harsh environmental conditions. Innovative studies in these areas will be of great importance for the increasing needs in the future.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

All authors have equal contributions. The authors have prepared all the chapters together.

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