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Research on X-Ray Image Acquisition Technology of High Voltage Transmission Tower Fittings Based on UAV

Libo Liu [1], Jiafeng Chen [1], Lei Yu [1], Guangze Zhu [1,*], Yanchen Cui [1], Zhicheng Wang [1], Jiaqiang Sun [1], Kangxian Tang [1] and Jilei Cai [1]

[1] Zhejiang Power Transmission and Transformation Engineering Co., Ltd., Hangzhou, Zhejiang, China
* Correspondence: Guangze Zhu, Zhejiang Power Transmission and Transformation Engineering Co., Ltd., Hangzhou, Zhejiang, China

Abstract: The safe and stable operation of high-voltage transmission lines is vital to the nation's energy supply, and hidden defects in transmission tower hardware pose a significant risk of major accidents. Traditional detection methods are inefficient, risky, incomplete, and unable to detect internal defects. To address these challenges, this paper introduces and explores an innovative X-ray imaging technology for high-voltage transmission tower hardware using a drone platform. The core of this technology is a high-performance, lightweight micro X-ray imaging system integrated into a drone, which combines high-precision positioning and stable hovering control, stringent radiation safety measures, and efficient image transmission and processing. This system enables non-contact, non-destructive imaging of key tower hardware. The study details the overall architecture design, key component selection, precise positioning and navigation, radiation field modeling, dose control strategies, and image acquisition and transmission methods adapted for the drone platform. Through systematic laboratory testing, simulation environment validation, and on-site application, the technology has been proven to effectively capture clear X-ray images of the internal structure of high-voltage tower hardware, significantly improving the accuracy and efficiency of defect detection, and greatly reducing the safety risks for workers. This technology provides strong technical support for intelligent and precise inspections of transmission lines, with significant engineering application value and broad prospects.

Keywords: UAV; high-voltage transmission line; hardware defects; X-ray imaging; nondestructive testing

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1. Introduction

As the energy artery of modern society, the safe and reliable operation of high-voltage transmission networks is crucial to the national economy and social stability. Transmission towers, which serve as the core support structures for overhead lines, are equipped with auxiliary hardware that plays a vital role in mechanical load transfer and electrical connections. These hardware components are frequently exposed to harsh natural environments and strong electromagnetic fields, making them highly susceptible to damage such as fatigue cracks, internal casting defects, material degradation, corrosion, wear, and loosening. These defects, especially those hidden within the materials, are often difficult to detect through routine external inspections and can lead to catastrophic events like hardware fractures, insulator detachment, tower collapses, and line breaks, resulting in significant economic losses and severe social impacts. Therefore, developing efficient, precise, and safe internal condition detection technologies for hardware is of great practical significance and urgent need to ensure grid safety, enable condition-based maintenance, and prevent major accidents [1-4].

Currently, the main methods for inspecting transmission tower hardware include manual tower inspections, infrared thermal imaging, ultraviolet corona detection, ground wire robot inspections, and traditional X-ray inspection vehicles. Manual tower inspections are inefficient, highly dangerous, and heavily dependent on human experience, making them ineffective for detecting internal defects. Infrared and ultraviolet inspections primarily focus on electrical connection abnormalities or surface discharges but are less sensitive to mechanical internal defects. Ground wire robots mainly inspect ground wires and accessories, making it difficult to cover the main hardware of the tower. Traditional X-ray inspection equipment is bulky, requires close-range operations, and is significantly limited by terrain, posing radiation safety challenges, which makes it difficult to widely apply in complex transmission corridors. In recent years, drone technology has made significant progress in power line inspections, being widely used for visible light inspections, infrared temperature measurements, and ultraviolet flaw detection, greatly improving inspection efficiency and safety. However, existing drone inspection methods are still primarily limited to checking the appearance and surface condition of equipment, with a severe lack of non-destructive flaw detection capabilities for the internal structure of hardware. Therefore, integrating advanced X-ray non-destructive testing technology with flexible and efficient drone platforms to develop a new inspection technology that can non-contactally obtain images of the internal structure of hardware has become an important research direction and technical breakthrough point in the field of intelligent power equipment inspection [5-9].

This paper addresses the urgent need for detecting internal defects in high-voltage transmission tower hardware and the limitations of current technologies. It proposes a drone-based X-ray imaging technology for high-voltage transmission tower hardware. The research aims to design and implement a safe, reliable, efficient, and practical drone-mounted X-ray imaging system and its associated operational methods, addressing key technical challenges such as lightweight integration, precise positioning with anti-shaking, radiation safety protection, and stable image acquisition and transmission. This study will open a new avenue for non-destructive testing of transmission line hardware, significantly enhancing the intelligence and safety assurance capabilities of power grid operations [10-12].

2. Overall System Design

To build a set of UAV-based X-ray image acquisition system for high-voltage transmission tower fittings, it is necessary to clarify its core requirements in the complex power inspection environment. The whole system is mainly composed of the following subsystems working closely together:

1) Subsystem of UAV flight platform: As the carrier and motion actuator of the whole system, industrial-grade UAV platform with high load, long endurance, strong wind resistance, high stability and rich expansion interface is selected to provide basic capabilities such as flight, hover and attitude adjustment.
2) Micro X-ray Imaging Subsystem: This is the core detection unit of the system, consisting of a miniaturized and lightweight pulsed micro-focus X-ray source and a high-sensitivity, high-resolution, low-power digital flat panel detector. These components are integrated under the drone using a precise rigid structure and vibration reduction devices, maintaining a fixed geometric relationship. The subsystem generates X-rays and receives the signals after they penetrate the metal parts to produce digital images.

3) The precise positioning and navigation subsystem integrates a high-precision RTK-GPS module to provide absolute position information, an inertial measurement unit (IMU) to sense the attitude, and a laser rangefinder or machine vision module to provide precise relative distance and orientation information with the tower components. Together, these components form a multi-sensor fusion system for high-precision positioning and navigation, ensuring the drone's precise spatial position in front of the target hardware.
4) Mission planning and flight control subsystem: It operates on the ground station or airborne computer, is responsible for planning the optimal flight path and target position of each detection point according to the detection mission, and generates accurate control instructions to drive the UAV platform to complete autonomous flight, precise positioning and stable hover.
5) Image acquisition, processing and transmission subsystem: including the airborne image acquisition control circuit, preprocessing unit (such as noise reduction, format conversion) and high-speed wireless image transmission module, as well as ground station image reception, display, storage and post-processing software to ensure real-time, reliable and high-quality transmission and recording of image data.
6) The radiation monitoring and safety protection subsystem consists of a wireless radiation dosimeter mounted on the UAV and deployed in the operation area. It monitors the environmental radiation dose rate in real time, and immediately alarms and links the control system to stop exposure or evacuate if the level exceeds the standard. The system design includes necessary local shielding measures and strictly follows the three principles of radiation protection: time, distance, and shielding.

3. Key Technology Research

3.1. Miniature and Lightweight X-Ray Imaging System Integration Technology

The primary prerequisite for integrating a drone is the significant lightweight and highly integrated X-ray imaging system. This involves the rigorous selection and optimization of core components, such as the — X-ray source and detector. Micro-focus pulsed X-ray sources based on carbon nanotube cold cathodes are preferred due to their compact size, light weight, high instantaneous power, fast switching response, no need for preheating, and relatively low power consumption, making them ideal for the intermittent operation mode of drone platforms. For the detector, amorphous silicon/selenium digital flat panel detectors or high-performance CMOS/CCD detectors are the top choices due to their excellent imaging performance, reasonable weight, and digital output characteristics. To achieve system integration, a precise mechanical installation structure must be designed to ensure that the ray source focus, the critical area of the inspected metal parts, and the detector imaging plane strictly adhere to the geometric projection law and maintain this rigid relationship in complex flight vibration environments. This requires using high-strength lightweight materials to create supports and integrating high-performance passive or active vibration reduction devices to effectively isolate the vibrations caused by the drone's rotor and aerodynamic disturbances from affecting image clarity. Additionally, the operation of the micro X-ray source generates electromagnetic interference (EMI), and drones operate in a strong industrial frequency electromagnetic field environment. Therefore, strict electromagnetic compatibility (EMC) design is necessary, including good shielding of the X-ray high-voltage generator, optimized wiring design, the use of shielded cables and connectors, and the addition of filtering circuits to prevent internal system interference or functional abnormalities caused by external field strength.

3.2. UAV Precise Positioning and Stable Hover Control Technology

The key to obtaining clear X-ray images lies in the exposure moment, where the drone must maintain extremely high precision and stability relative to the target hardware. This is achieved through the integration of multiple sensors for high-precision positioning and advanced control strategies. First, real-time dynamic differential GPS technology provides centimeter-level absolute positioning. However, GPS alone is insufficient for millimeter-level relative positioning between the drone and the tower components. Therefore, it is necessary to integrate various relative positioning sensors: laser rangefinders can accurately measure the distance from the drone to specific points on the tower; visual modules can provide relative position and attitude angle information through feature point matching or target recognition. By combining high-precision inertial measurement unit (IMU) data with Kalman filtering and other data fusion algorithms, the precise six-degree-of-freedom pose of the drone relative to the target hardware can be calculated in real time. In terms of control, a specialized hovering control algorithm optimized for X-ray imaging must be developed. This algorithm must not only resist wind disturbances but also minimize the fluctuations in the drone's attitude angle and position drift within the brief time window before and after the exposure command is issued, to prevent image blurring caused by motion artifacts.

3.3. Radiation Safety Protection and Dose Control Technology

Radiation safety is the lifeline of this technology, and a comprehensive protection system must be established. First, based on the selected X-ray source parameters, an accurate spatial distribution model of the radiation dose field should be created. The model must account for the scattering effect of the tower's steel structure on the rays. Based on this dose field model, strict safety distances and heights for operations should be set: a three-dimensional "danger zone" centered on the radiation source should be delineated, where the radiation dose rate may exceed limits; the minimum safe distance that ground operators must maintain while the drone hovers should be defined; and the safe flight altitude of the drone relative to the operator and the public should be determined. On the hardware side, necessary local shielding designs for the X-ray source on the drone platform should be implemented to strictly limit the main ray beam to the direction towards the detector and target metal parts, and to minimize leakage radiation in other directions. Strict safety controls must be enforced during the operation process: the site must be thoroughly cleared before the operation to ensure no personnel remain in the danger zone; prominent radiation warning signs and warning lines should be set up; operators must wear personal dosimeters and receive adequate training; detailed emergency response plans should be developed. All operations must strictly comply with the national "Regulations on Safety and Protection of Radioactive Isotopes and Radiation Devices" and related laws and regulations.

3.4. Image Acquisition, Processing and Transmission Technology

To adapt to the dynamic characteristics of UAV platforms, it is essential to design a reliable image acquisition and transmission link. Image acquisition must be precisely synchronized with X-ray exposure, typically triggered by the flight control system or ground station after confirming the UAV's stable hover. The detector must have rapid readout capabilities to minimize the time required for a single imaging session. To address the inevitable minor residual vibrations or geometric distortions caused by the UAV platform or non-ideal imaging angles, image preprocessing is necessary at either the airborne or ground station. Preprocessing algorithms include: vibration and blur correction based on IMU or image features, geometric distortion correction, and basic image denoising and contrast enhancement to optimize visual quality. Image quality is evaluated using objective metrics such as spatial resolution, contrast sensitivity, signal-to-noise ratio (SNR), and contrast-to-noise ratio (CNR) to ensure that images meet the requirements for defect identification. Image transmission faces challenges related to bandwidth and reliability.

4. Experimental Verification and Result Analysis

In order to comprehensively evaluate the performance, safety and practicability of the proposed UAV X-ray hardware detection system, this study designed a systematic experimental verification scheme.

A system prototype was constructed in a controlled laboratory environment. The core components, including the UAV platform, miniature X-ray source, flat panel detector, high-precision RTK module, laser rangefinder, and radiation dosimeter, were successfully integrated. The radiation dosimeter was rigorously calibrated. Laboratory functional tests confirmed that all basic functions of the system operated normally: the UAV could fly and hover stably; the positioning system achieved centimeter-level accuracy under static conditions; the X-ray could be reliably triggered for exposure as instructed; the detector could capture images and transmit them wirelessly with clarity; radiation monitoring data was displayed in real time. The hover stability test showed that, under simulated light wind conditions, the anti-shake control algorithm used by the system could keep the position drift within ±5mm and the attitude angle fluctuation <0.3 degrees during exposure, meeting the basic imaging requirements. Radiation dose field measurements were conducted using a standard ionization chamber at various distances in multiple directions, and the actual measurement results closely matched the model predictions, verifying the accuracy of the dose field model. Local shielding measures were proven to effectively reduce lateral leakage radiation.

Standard test block imaging test: The system's spatial resolution is verified to be better than 2.5 LP/mm using a line pair test card. The system also performs imaging on aluminum alloy and steel test blocks with artificial defects. The results show that the system can clearly identify cracks with a width of at least 0.2mm, porosity with a diameter of at least 1.0mm, and grooves with a depth of at least 1.5mm, demonstrating its basic defect detection capability.

Subsequently, a simulated iron tower environment was set up outdoors, and real transmission line hardware was installed. Typical defects were artificially created on these hardware components. The drone system followed the planned path to inspect multiple hardware points. The imaging results clearly revealed the internal structural features of the hardware. The artificial defects were clearly visible in the X-ray images, with good contrast, demonstrating the system's capability to effectively detect internal defects in actual hardware. Imaging comparison experiments from different angles and distances also provided practical data for optimizing the illumination parameters. The operation efficiency statistics showed that it took an average of 3-5 minutes to complete the inspection of one hardware point during a single hover, and a single flight could inspect 5-7 key points, significantly improving efficiency compared to manual tower inspections (Figure 1).

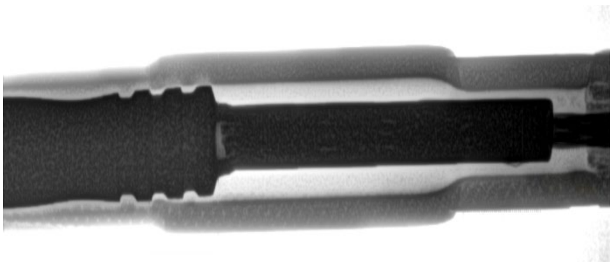

Figure 1. Jig Inspection Image.

5. Conclusion and Prospect

This paper addresses the significant need for detecting hidden defects inside high-voltage transmission tower fittings and the limitations of traditional methods. It systematically explores X-ray image acquisition technology based on a drone platform. The study successfully designed and implemented a comprehensive detection system that integrates drone flight, micro X-ray imaging, high-precision positioning and navigation, radiation safety monitoring, and image transmission processing. By overcoming key technical challenges such as the integration of lightweight X-ray systems with vibration reduction, precise positioning and anti-jamming hover control using multiple sensors, modeling of radiation dose fields, and comprehensive safety protection, a standardized operational process has been established. Laboratory tests, simulation environment validations, and on-site applications have consistently shown that this system can efficiently and reliably obtain clear X-ray images of the internal structures of key fittings in high-voltage towers, ensuring radiation safety. It has good detection capabilities for typical internal defects, significantly enhancing detection efficiency and safety.

The primary innovations of this study include: (1) the first proposal and full implementation of an innovative solution that integrates a drone platform with micro X-ray imaging technology for non-destructive testing of internal components in high-voltage transmission tower hardware; (2) overcoming the technical challenges of lightweight, vibration-resistant, and electromagnetic compatibility in industrial-grade drones equipped with X-ray systems; (3) developing a high-precision relative positioning method that combines RTK-GPS, laser ranging, and machine vision, along with a robust hovering control strategy tailored for X-ray imaging.

Despite the significant achievements, this study still has certain limitations: due to the current battery technology and the payload capacity of the drone platform, the number of effective detection points per flight needs to be increased; for extremely complex structures or those severely obstructed by other components, finding the optimal illumination angle remains a challenge; the system's adaptability and reliability in extreme weather conditions need further improvement.

Looking ahead, the research will focus on the following areas: (1) Continuous weight reduction and improved endurance: exploring the use of new batteries with higher energy density, optimizing structural design to further reduce system weight, and extending the duration and coverage of a single flight. (2) Enhancing intelligent automation: deeply integrating artificial intelligence technology to develop deep learning-based X-ray image analysis algorithms for automatic identification, localization, and classification of common hardware defects. (3) Improving adaptability in complex environments: researching stronger wind resistance control algorithms and exploring more reliable communication and positioning solutions in strong electromagnetic interference environments.

References

1. F. Abdollahi-Mamoudan, C. Ibarra-Castanedo and X. P. V. Maldague, "Non-Destructive Testing and Evaluation of Hybrid and Advanced Structures: A Comprehensive Review of Methods, Applications, and Emerging Trends," *Sensors*, vol. 25, no. 12, p. 3635, 2025, doi: 10.3390/s25123635.
2. M. I. Ahmad, M. H. Ab. Rahim, R. Nordin, F. Mohamed, A. Abu-Samah and N. F. Abdullah, "Ionizing Radiation Monitoring Technology at the Verge of Internet of Things," *Sensors*, vol. 21, no. 22, p. 7629, 2021, doi: 10.3390/s21227629.
3. S. Zhang, Y. He, Y. Gu, Y. He, H. Wang and B. Zhou, "UAV based defect detection and fault diagnosis for static and rotating wind turbine blade: a review," *Nondestruct. Test. Eval.*, vol. 40, no. 4, pp. 1691–1729, 2024, doi: 10.1080/10589759.2024.2395363.
4. J. C. Jianye, Y. Gu, J. Liang, W. Qin, K. Zhu and T. Liu, "Research on X-ray Live Inspection Method for Tensile Clamps of Transmission Lines," 2022 7th Asia Conf. Power Electr. Eng. (ACPEE), Hangzhou, China, 2022, pp. 1441-1445, doi: 10.1109/ACPEE53904.2022.9784061.
5. S. Lian, N. Wang, G. Yu and Y. Peng, "Research on X-ray Detection Technology for Connection Fittings of UHV Transmission Lines based on helicopter live work," 2022 5th Int. Conf. Electron. Electr. Eng. Technol. (EEET), Beijing, China, 2022, pp. 76-82, doi: 10.1109/EEET58130.2022.00022.

6. W. Qian, G. Yu, C. Yuan, K. Zhu, J. Liang and T. Liu, "Research on Electromagnetic Interference Protection of X-ray Detecting Device for Tension Clamp of Transmission Line," 2022 7th Asia Conf. Power Electr. Eng. (ACPEE), Hangzhou, China, 2022, pp. 1436-1440, doi: 10.1109/ACPEE53904.2022.9783803.
7. N. Mohd Zainuddin et al., "Review of Thermal Stress and Condition Monitoring Technologies for Overhead Transmission Lines: Issues and Challenges," *IEEE Access*, vol. 8, pp. 120053-120081, 2020, doi: 10.1109/ACCESS.2020.3004578.
8. H. Shao, J. Lv, J. Wang, Z. Zeng and S. Qu, "Automatic crimping state classification in X-ray images of crimped tension clamp," *Nondestruct. Test. Eval.*, vol. 40, no. 2, pp. 610–626, 2024, doi: 10.1080/10589759.2024.2326610.
9. P. Nooralishahi, C. Ibarra-Castanedo, S. Deane, F. López, S. Pant, M. Genest, N. P. Avdelidis and X. P. V. Maldague, "Drone-Based Non-Destructive Inspection of Industrial Sites: A Review and Case Studies," *Drones*, vol. 5, no. 4, p. 106, 2021, doi: 10.3390/drones5040106.
10. X. Huang, Y. Wu, Y. Zhang and B. Li, "Structural Defect Detection Technology of Transmission Line Damper Based on UAV Image," *IEEE Trans. Instrum. Meas.*, vol. 72, pp. 1-14, 2023, Art no. 3504314, doi: 10.1109/TIM.2022.3228008.
11. Z. Jia, Y. Ouyang, C. Feng, S. Fan, Z. Liu and C. Sun, "A Live Detecting System for Strain Clamps of Transmission Lines Based on Dual UAVs' Cooperation," *Drones*, vol. 8, no. 7, p. 333, 2024, doi: 10.3390/drones8070333.
12. D.-W. Liu, J.-L. Yao, H.-Y. Ni, C. Pan and W.-X. Yan, "A Portable X-ray Flaw Detection Equipment with High Voltage for Transmission Line," 2022 IEEE Int. Conf. High Volt. Eng. Appl. (ICHVE), Chongqing, China, 2022, pp. 1-4, doi: 10.1109/ICHVE53725.2022.9961550.