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Defect Detection Technology of Tension Clamps Based on UAV

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Abstract: The tension clamp, a critical component of transmission lines, can lead to major safety incidents if its defects are not addressed. Traditional manual inspections are inefficient and risky. This paper introduces an intelligent inspection technology for tension clamps using drones, which employs a quad-copter equipped with high-definition visible light and infrared dual-sensor systems. By integrating autonomous flight path planning, this system can collect data from multiple angles at close range. For typical defects such as cracks, rust, and overheating, a two-stage recognition model has been developed, combining YOLOv5 object detection with an improved ResNet34 classification algorithm, and incorporating attention mechanisms to enhance the extraction of features from small targets. Experiments show that on a test set of 2,368 annotated images, the system achieves a positioning accuracy of 96.2%, an average defect recognition accuracy of 92.7%, and reduces the detection time for a single base tower to 8 minutes. This technology significantly enhances inspection efficiency and safety, offering a new solution for the intelligent operation and maintenance of transmission lines.

Keywords: UAV inspection; tension clamp; defect detection; deep learning; infrared thermal imaging; transmission line maintenance

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1. Introduction

1.1. Research Background and Significance

The tension clamp, which bears the mechanical load and conducts electricity for transmission lines, can lead to line breakage due to its defects. Traditional inspection methods, such as manual climbing or telescope observation, are fraught with high safety risks, low efficiency, and a high rate of missed inspections. Drone technology, with its flexibility and close-range observation capabilities, effectively addresses these issues and holds significant engineering value for ensuring the safe operation of power grids [1-9].

1.2. Research Status at Home and Abroad

Internationally, the U.S. EPRI has achieved drone-based insulation insulator damage detection (2020), but the detailed inspection of tension line clamps is still in the experimental stage [10-15]. In China, the Southern Power Grid (2022) has attempted visible light inspections, with defect identification relying on manual image analysis. The current research challenges include:

1) Difficulty in accurately locating components in complex backgrounds.

2) Insufficient extraction of millimeter-level defect features.
3) Inadequate integration and application of multi-source data [16-20].

1.3. Research Content and Objectives

This study proposes:

1) To build a dual-light collaborative acquisition system for UAVs.
2) To develop an automatic defect recognition algorithm based on deep learning.
3) To establish a standardized detection process.

The goal is to achieve a defect recognition accuracy of more than 90%, improve the detection efficiency by more than three times, and form a technology paradigm that can be generalized.

2. Construction of UAV Detection System and Image Acquisition

2.1. Hardware System Integration

The DJI Matrice 300 RTK is used as the carrier platform, equipped with a high-resolution visible light camera and an FLIR T1040 infrared thermal imager. The dual sensors are synchronized through a custom gimbal, ensuring that the temperature measurement error is controlled within ± 2℃. A dual-link system of 4G and video transmission ensures real-time data feedback.

2.2. Refinement of Operation Process

1) Route Planning: Construct a 3D model of the tower based on laser point clouds, automatically generate a circling route, and set up 8 hovering observation points for the tension line clamps.
2) Collection Specifications: The visible light shooting resolution is 4096x2160, the infrared acquisition frequency is 5Hz, and a polarizing filter is used when the illumination intensity exceeds 50,000 lux.
3) Obstacle Avoidance Strategy: Utilize millimeter-wave radar and visual perception fusion for obstacle avoidance, and switch to anti-magnetic shielding mode in electromagnetic interference environments.

2.3. Data Preprocessing

The improved MSRCR algorithm is used to eliminate the light unevenness, and multi-view image stitching is realized through SIFT feature matching. The infrared data is corrected for non-uniformity and temperature calibration, and a pixel-level registration model of visible light and infrared is established, which lays the foundation for the dual-light fusion analysis shown in Figure 1.

Figure 1. Data Acquisition Work.

3. Tension Clamp Defect Identification Algorithm

3.1. Target Positioning Module

A lightweight YOLOv5s network is constructed, and the coordinate attention mechanism is introduced to enhance the spatial positioning ability. After transfer training on the self-made data set, the detection accuracy of the model for the main body of the tension clamp reaches 96.2%, and the inference speed is 42fps.

3.2. Multi-Dimensional Defect Feature Library

Establish the discrimination criteria of four kinds of defects (Table 1):

Table 1. Defect Classification.

Type of defect	Visible light features	Infrared signature
flaw	Linear texture (aspect ratio > 5)	-
rustiness	Brownish-red patches (HSV: 0-10°)	Temperature difference ≤ 1℃
superheat	Metallic color change (ΔL* > 15)	Temperature rise > 10℃ (phase to phase)
The bolt is loose	Angular offset (>5°)	Local hot spots

3.3. Hierarchical Recognition Model

The ResNet34 serves as the backbone network, with improvements including:

1) Integrating an ECA attention module in Stage3.
2) Employing focal loss to address sample imbalance.
3) Adding deformable convolution to enhance the extraction of deformation features.

The model outputs defect types and confidence levels, which are then filtered using NMS to generate detection reports.

4. Experimental Verification

4.1. Test Environment

In the 500kV Jiande power transmission and transformation project, 30 base towers were selected to collect 2368 effective images and 412 defect samples. The hardware configuration was Intel i7-11800H/RTX 3080, and the software environment was PyTorch1.10 + OpenCV4.5.

4.2. Performance Indicators

The performance indicators are shown in Table 2.

Table 2. Table of Performance Indicators.

Metric	Object detection	Defect identification
precision (%)	96.2	92.7
recall (%)	94.8	89.3
inference speed (ms)	23.8	51.6

4.3. Result Analysis

The system successfully identified 382 defects with a leakage rate of 7.3%, among which the overheating defect identification rate reached 95.6%. The typical misjudgment was caused by the reflection interference of water accumulation in heavy rain weather. Compared with traditional methods, the detection efficiency was increased by 3.8 times and the cost was reduced by 67%.

5. Conclusion and Prospect

This study systematically proposes an intelligent detection technology system for tension line clamp defects using drones. By integrating high-resolution visible light and infrared thermal imaging sensors on a quadcopter platform, it constructs a refined data collection system suitable for the complex environment of transmission lines. An innovative two-stage recognition model has been developed, combining YOLOv5 object detection with an improved ResNet34 classification algorithm. The model enhances feature extraction for millimeter-level defects by incorporating coordinate attention mechanisms and deformable convolutional layers, and effectively mitigates sample imbalance issues through the use of Focal Loss function. Field validation at 30 towers of the 500kV Jiande Transmission and Transformation Project demonstrated that the system achieved a 96.2% (mAP@0.5) accuracy in locating the main body of tension line clamps among 2,368 test images. The comprehensive recognition accuracy for four typical defects — cracks, rust, overheating, and loose bolts — reached 92.7%, and the inspection time for a single tower was reduced to 8 minutes, improving efficiency by 3.8 times compared to traditional manual inspections. The core value of this technology lies in solving the industry challenge of detecting small power hardware targets under complex background interference — by establishing a multi-dimensional discriminant system of visible light texture features and infrared temperature rise features, combined with a pixel-level registration model of dual-light data, significantly enhancing the reliability of defect discrimination. In terms of engineering application, the pilot project in Zhejiang Power Grid successfully warned of 7 major defects, directly avoiding economic losses exceeding 2 million yuan. Calculations show that full-scale promotion could reduce the line fault rate by more than 35%, providing a reusable technical paradigm for the intelligent operation and maintenance of transmission lines.

The current research faces three main limitations: Firstly, the temperature measurement accuracy of infrared sensors in strong electromagnetic interference environments can fluctuate by ±5°C, which affects the quantitative diagnosis of overheating defects; Secondly, extreme weather conditions such as heavy rain and dense fog degrade the quality of visible light images, increasing the false detection rate to 18.6%; Lastly, the ability to identify rare defects is insufficient, necessitating the expansion of the heterogeneous image database. Future research will focus on four key areas: Firstly, developing composite shielding sensor modules resistant to electromagnetic interference, combined with adaptive filtering algorithms to enhance data robustness; Secondly, constructing a multi-modal small-sample learning framework based on Vision Transformer, using transfer learning to overcome the challenge of scarce rare defect samples; Thirdly, integrating laser point clouds with BIM technology to create digital twins of tension line clamps, enabling the prediction of defect evolution trends and life assessment; Fourthly, developing a cluster drone collaborative operation platform, utilizing task allocation optimization algorithms to achieve autonomous networked inspections over hundreds of kilometers. With the implementation of the "Technical Guidelines for Power Drone Patrol Inspection" (DL/T 2025-2024), the technical standards and datasets developed in this study will serve as important references for the industry, ultimately facilitating the strategic shift from "post-event repair" to "pre-event prevention" in power transmission inspection.

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