# Research on Construction of Hyperspectral Sample Library for Insulators and Application of Lightweight Detection Device

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**ABSTRACT** This paper conducts research on the construction of a hyperspectral sample library for insulators and the development of a lightweight detection device. Firstly, the principle of hyperspectral imaging and the spectral response laws of different insulator defects are analyzed. A standardized experimental platform is built to complete the acquisition, preprocessing and annotation of multi-type, multi-defect and multi-working-condition data. The samples are expanded through spectral and spatial data augmentation, and a high-quality special hyperspectral sample library for insulators is constructed. Secondly, the detection model is lightweight optimized by combining pruning, quantization, knowledge distillation and other methods, which reduces the computational overhead of the model while ensuring the accuracy. Finally, the software and hardware co-design is completed, an integrated lightweight detection device is developed, and laboratory and field tests are carried out. The experimental results show that the sample library constructed in this paper has high annotation quality and good generalization performance. the inference speed of the optimized model meets the requirements of real-time detection. the self-developed device has low power consumption and strong portability, and has a high recognition rate for both macroscopic and hidden defects of insulators. Its comprehensive performance is superior to traditional detection methods, which can be effectively applied to the field inspection scenario of transmission lines and has high engineering application value.

**INDEX TERMS** Insulator, Hyperspectral Imaging, Sample Library, Lightweight Algorithm, Detection Device

## I. INTRODUCTION

### A. RESEARCH BACKGROUND AND SIGNIFICANCE

AGAINST the background of the construction of the new power system, the coverage of high-voltage and ultra-high-voltage transmission lines continues to expand, and the service environment of the lines is becoming increasingly complex. As the core insulating and load-bearing component of transmission lines, the operating state of insulators is directly related to the safe and stable operation of the power grid. Long-term outdoor service makes them prone to various defects due to contamination, aging, mechanical damage and complex meteorological conditions, which can easily lead to power accidents such as flashover and tripping. Therefore, accurate and efficient defect detection of insulators is a key link in power grid operation and maintenance [1].

Current mainstream traditional technologies such as manual inspection, infrared, visible light and ultrasonic detection have shortcomings such as single detection dimension, weak anti-interference ability, poor recognition ability for hidden defects and low inspection efficiency, which are difficult to meet the demand for intelligent inspection under complex working conditions [2].

Hyperspectral imaging technology has the advantages of spectral-spatial integration, high spectral resolution and rich feature information. It can capture the changes in the micro-physical and chemical properties of insulators, and can effectively identify weak and hidden defects that are difficult to detect by traditional methods. At the same time, most existing hyperspectral detection technologies rely on large laboratory equipment and complex computing power models, which have problems such as poor portability and difficulty in field deployment [3].

Therefore, building a lightweight and field-deployable hyperspectral detection system has important theoretical and engineering application value for promoting the upgrading of intelligent inspection of power grid insulators, reducing operation and maintenance costs, and ensuring the safe operation of the power system.

### B. RESEARCH STATUS AT HOME AND ABROAD

#### 1) Research Progress of Insulator Defect Detection Technology

At present, a large number of studies have been carried out on insulator defect detection at home and abroad. Traditional detection methods combined with machine vision and deep learning can effectively identify apparent defects such as macroscopic damage and flashover of insulators [4], but they generally rely on two-dimensional image features, which are difficult to capture the micro-changes of materials and have limited ability to identify early hidden defects [4].

#### 2) Research Status of Hyperspectral Sample Library Construction Technology

In terms of data support for hyperspectral detection, most existing public datasets are concentrated in the fields of remote sensing and agriculture [5], and there is a serious lack of standardized hyperspectral sample libraries for transmission insulators. Existing power samples have problems such as single defect type, insufficient coverage of working conditions and non-standard annotation, which restrict the training accuracy and generalization ability of detection algorithms [6].

#### 3) Development Status of Hyperspectral Lightweight Detection Devices

In recent years, with the development of embedded technology and lightweight deep learning technology, some scholars have begun to explore the miniaturization design of hyperspectral detection equipment [7].

Most existing hyperspectral detection studies focus on the simulation optimization of algorithm lightweight, with insufficient consideration of hardware integration and field working condition adaptation. Most equipment has large volume and power consumption and poor real-time performance, which is difficult to meet the demand for on-site inspection deployment

### C. RESEARCH CONTENT

Aiming at the deficiencies of existing research, this paper takes the intelligent defect detection of transmission line insulators as the core goal and constructs standardized hyperspectral samples for insulators. The specific research contents are as follows:

First, sort out the theoretical basis of hyperspectral detection of insulators, and analyze the spectral response mechanism of different defects and data processing methods.

Second, build a standardized data acquisition platform, complete the acquisition, preprocessing, annotation and expansion of hyperspectral data of insulators under multiple working conditions, construct a high-quality special sample library and complete the quality evaluation.

Third, design a lightweight defect detection algorithm, and realize algorithm optimization and embedded adaptation through model pruning, quantization and knowledge distillation.

Fourth, complete the integrated design and debugging of the software and hardware of the detection device, and verify the comprehensive performance of the sample library, algorithm and device through laboratory simulation and field application tests.

TABLE 1. Parameter Comparison of Mainstream Lightweight Hyperspectral Imaging Equipment

| Imaging Equipment Type | Wavelength Range/nm | Spectral Resolution/nm | Weight/g | Power Consumption/W |
|---|---|---|---|---|
| Push-broom Hyperspectral Camera | 400–1000 | 2.8 | 580 | 3.5 |
| Snapshot Hyperspectral Camera | 450–950 | 5.0 | 320 | 2.0 |
| Filter-based Hyperspectral Camera | 420–980 | 10.0 | 180 | 1.2 |

## II. THEORETICAL BASIS OF HYPERSPECTRAL IMAGING AND DEFECT DETECTION FOR INSULATORS

### A. PRINCIPLE OF HYPERSPECTRAL IMAGING TECHNOLOGY

#### 1) Composition of Hyperspectral Imaging System

The hyperspectral imaging system is mainly composed of four parts: optical imaging module, spectral splitting module, image sensor, and data acquisition and transmission module [8].

The optical module is responsible for collecting the reflected light of the target object. The spectral splitting module decomposes the continuous light into tens to hundreds of narrow-band spectral signals through gratings, filters and other devices. The image sensor completes the synchronous acquisition of spectral signals and spatial image signals, and finally outputs three-dimensional hyperspectral data by the data transmission module.

The parameter comparison of current mainstream lightweight hyperspectral imaging equipment is shown in Table 1.

#### 2) Spectral Resolution and Spatial Resolution

Spectral resolution refers to the minimum spectral band interval that the equipment can distinguish, which directly determines the fineness of spectral features. The higher the resolution, the more capable it is to capture the subtle spectral changes caused by insulator defects [9].

Spatial resolution determines the detail presentation ability of images and affects the positioning accuracy of insulator defect areas.

In this study, a snapshot hyperspectral imaging equipment is selected, which takes into account spectral accuracy, spatial accuracy and equipment lightweight requirements, and can meet the index requirements of field insulator defect detection.

#### 3) Characteristics of Hyperspectral Data Cube

The output data of hyperspectral imaging is a three-dimensional data cube, including two-dimensional spatial dimensions and one-dimensional spectral dimension [10].

The spatial dimension completely retains the shape, defect position and morphological characteristics of insulators, and the spectral dimension contains the continuous spectral reflectance curve of each pixel, which can reflect the physical and chemical properties of insulator materials.

The spectral-spatial integrated data characteristic realizes the combination of insulator morphology detection and material property detection, providing data support for the identification of hidden defects.

### B. ANALYSIS OF SPECTRAL CHARACTERISTICS OF INSULATOR MATERIALS

#### 1) Common Insulator Types and Material Characteristics

The mainstream insulators in current transmission lines include three types: porcelain insulators, glass insulators and composite insulators [11].

Porcelain insulators have dense texture and stable insulation, but are prone to aging and cracking.

Glass insulators have high mechanical strength and good self-cleaning property, but are prone to self-explosion and contamination deposition during long-term service.

Composite insulators are light in weight and strong in anti-pollution flashover ability, which are the mainstream application type at present. However, they are prone to surface aging, pulverization and damage defects during long-term service.

The three types of insulators have great differences in material composition and different intrinsic spectral reflectance characteristics.

#### 2) Spectral Reflectance Characteristics of Normal Insulators

Normal defect-free insulators have uniform materials and smooth surfaces, with smooth and stable spectral reflectance curves. The spectral data of normal insulators of the same batch and under the same working conditions have extremely high similarity, and there is no obvious band mutation.

Porcelain insulators have a stable and high reflectance in the visible-near infrared band, glass insulators have a moderate reflectance, and composite insulators have a slightly lower reflectance and smaller curve fluctuation due to the characteristics of the surface silicone rubber material.

#### 3) Mechanism of Spectral Difference of Typical Defective Insulators

After defects occur in insulators, the surface microstructure, material composition and surface state change, which directly leads to shifts, fluctuations and disappearance of characteristic peaks in the spectral reflectance curves.

Contamination defects will adsorb impurities and change the surface roughness, reducing the overall spectral reflectance. crack and damage defects will cause local spectral band reflection mutations. aging defects will lead to material oxidation, causing regular shifts in the spectral response of specific characteristic bands, which is also the core mechanism of hyperspectral technology for identifying insulator defects [12].

### C. HYPERSPECTRAL DATA PROCESSING AND DEFECT DETECTION ALGORITHMS

#### 1) Hyperspectral Data Preprocessing Methods

Hyperspectral data collected in the field is easily interfered by illumination, noise and equipment errors, so preprocessing is required to improve data quality.

The core preprocessing methods include radiometric correction, geometric correction, noise removal, band selection and data normalization [13]:

Radiometric correction eliminates spectral deviations caused by illumination intensity and atmospheric scattering.

Geometric correction corrects image distortion during imaging.

Noise removal eliminates abnormal data generated by equipment dark current and environmental interference.

Band selection removes invalid noise bands and reduces data dimension.

#### 2) Spectral Feature Extraction Algorithms

Hyperspectral data has high dimension and strong information redundancy, so effective defect features need to be screened through feature extraction.

Common methods include principal component analysis, spectral derivative feature extraction, band ratio feature extraction, etc.

By extracting the sensitive spectral feature bands corresponding to insulator defects and eliminating redundant information, the computational efficiency and recognition accuracy of subsequent defect detection algorithms can be effectively improved.

#### 3) Lightweight Deep Learning Detection Models

Traditional deep learning detection models such as YOLOv4 and Faster R-CNN have large parameters and high computing power requirements, which cannot be adapted to embedded device deployment [14].

Lightweight detection models greatly reduce the model size and inference time while ensuring detection accuracy by simplifying the backbone network, optimizing the feature fusion structure and reducing convolution parameters [15].

This paper optimizes based on the lightweight YOLO series models, integrates the spectral attention mechanism, adapts to the feature distribution law of insulator hyperspectral data, and realizes high-precision and low-latency defect detection.

## III. CONSTRUCTION AND OPTIMIZATION OF HYPERSPECTRAL SAMPLE LIBRARY FOR INSULATOR

### A. OVERALL DESIGN SCHEME OF THE SAMPLE LIBRARY

1) Construction Objectives and Principles of the Sample Library

The construction of the sample library in this paper takes "standardization, diversification, high precision and scalability" as the core principles. The goal is to construct a special hyperspectral sample library for insulators adapted to the transmission line inspection scenario, covering mainstream insulator types, typical defect types and multiple field working conditions, solving the problems of existing sample data such as disorder, poor standardization and incomplete coverage, and providing high-quality data support for the training, verification and optimization of defect detection algorithms.

2) Architecture Design of the Sample Library

The sample library adopts a layered architecture design, which is divided into data storage layer, annotation management layer, feature analysis layer and application support layer.

The data storage layer stores original hyperspectral data, preprocessed data and augmented data.

The annotation management layer stores defect annotation files and quality verification records.

The feature analysis layer counts the spectral characteristics and distribution laws of samples.

The application support layer provides standardized data interfaces for algorithm training, model testing and device verification. The overall architecture is simple and efficient, with good scalability.

### B. HYPERSPECTRAL DATA ACQUISITION OF INSULATORS

1) Construction of Experimental Platform

An indoor standardized hyperspectral data acquisition experimental platform is built, which consists of a lightweight hyperspectral imaging equipment, an adjustable light source system, a precision stage and an environmental control module.

The adjustable light source can simulate different illumination intensities, and the environmental control module can adjust temperature and humidity to accurately restore complex field working conditions and ensure the authenticity and diversity of collected data.

2) Sample Preparation and Defect Type Classification

Three types of insulators commonly used in power grids, namely porcelain, glass and composite insulators, are selected as research samples, and common field defects are artificially simulated, including five typical defects: surface contamination, surface aging, micro-cracks, edge damage and flashover traces. Various defect samples have clear classification and clear grades. The sample classification statistics are shown in Table 2.

**TABLE 2.** Classification and Quantity Statistics of Insulator Defect Samples

| Insulator Type | Defect Type | Defect Grade | Number of Original Samples |
|---|---|---|---|
| Composite Insulator | Surface Contamination | Mild, Moderate, Severe | 320 |
| | Surface Aging | Mild, Severe | 280 |
| | Micro-cracks | Subtle, Obvious | 260 |
| | Edge Damage | Local, Large-area | 240 |
| | Flashover Traces | Mild, Severe | 220 |
| Porcelain/Glass Insulators | The above five defects | Corresponding grade division | 880 |

3) Standardized Data Acquisition Process

A unified data acquisition specification is formulated, the imaging distance, shooting angle and equipment parameters are fixed. The equipment spectral and geometric calibration is completed before acquisition, and the environmental parameters, insulator types and defect information are recorded synchronously during the acquisition process to ensure that all sample data have unified format, complete information and traceability, and guarantee the sample data quality from the source.

4) Data Acquisition Under Multiple Environmental Conditions

To improve the generalization ability of the sample library, multi-environment data acquisition is carried out by simulating complex field working conditions.

By adjusting the light source intensity to simulate sunny, cloudy and backlight illumination conditions, adjusting the humidity through the environmental module to simulate dry, humid and rainy environments, and completing data acquisition under different temperature working conditions, covering common field scenarios of power grid inspection.

### C. HYPERSPECTRAL DATA PREPROCESSING AND ANNOTATION

1) Noise Removal and Spectral Correction

Systematic preprocessing is performed on the original collected data. The median filtering algorithm is used to remove image spatial noise, and the spectral data correction is completed through dark current correction and whiteboard correction to eliminate data errors caused by equipment and environmental interference, ensuring that the spectral curve can truly reflect the material characteristics of insulators.

2) Data Normalization and Dimensionality Reduction

The maximum-minimum normalization method is used to uniformly map the spectral reflectance to the 0–1 interval to eliminate the difference in data dimensions.

The principal component analysis algorithm is used to reduce the dimension of high-dimensional hyperspectral data, retain the core characteristic bands, eliminate redundant information, and reduce the computing power consumption of subsequent algorithm training.

#### 3) Pixel-Level and Image-Level Defect Annotation

A two-dimensional annotation method is adopted. Image-level annotation is used for macroscopic damage and large-area contamination defects of insulators, and pixel-level fine annotation is used for hidden defects such as micro-cracks and mild aging to accurately locate the defect areas and defect types, adapting to the needs of different detection tasks.

#### 4) Annotation Quality Control Method

A quality control mechanism of multi-person cross-annotation and secondary verification is established. Two annotators independently annotate the same sample, review and correct the areas with annotation differences, and finally automatically verify the rationality of annotation boundaries through algorithms to eliminate problems such as missing annotation, wrong annotation and annotation deviation, and ensure the accuracy of annotation data.

### D. SAMPLE LIBRARY EXPANSION AND GENERALIZATION ENHANCEMENT

#### 1) Spectral Data Augmentation Technology

Aiming at the problems of high difficulty in hyperspectral sample collection and small number of scarce defect samples, spectral data augmentation technology is used to expand samples.

By means of slight shift of spectral curves, Gaussian noise superposition and fine adjustment of band weights, new spectral samples are generated without changing the essential characteristics of defects, enriching the diversity of sample spectral features.

#### 2) Spatial Data Augmentation Method

Combined with image spatial features, spatial augmentation methods such as rotation, flipping, random cropping and brightness fine-tuning are used to expand the diversity of sample spatial forms, avoid model training overfitting, and improve the adaptability of the model to different shooting angles and different illumination scenes.

After data augmentation, the total capacity of the sample library is increased to more than 3200 copies.

### E. QUALITY EVALUATION OF THE SAMPLE LIBRARY

#### 1) Sample Diversity Evaluation

The sample diversity is evaluated from four dimensions: insulator type, defect type, defect grade and environmental working condition. The sample library constructed in this paper completely covers three mainstream insulators, five typical defects, multi-gradient defect grades and multiple field working conditions. The sample distribution is balanced without obvious bias, and the diversity meets the needs of algorithm training and engineering testing.

#### 2) Annotation Consistency Verification

The Kappa coefficient is used to evaluate the annotation consistency. The measured Kappa coefficient of sample annotation reaches 0.92, indicating that the annotation results have high consistency and small errors, and the annotation quality is reliable, which can effectively support the training and verification of defect detection models.

## IV. DESIGN AND IMPLEMENTATION OF LIGHTWEIGHT HYPERSPECTRAL DETECTION DEVICE FOR INSULATORS

### A. OVERALL DESIGN OF THE DETECTION DEVICE

#### 1) Design Requirement Analysis

Combined with the engineering requirements of field transmission line inspection, the device needs to meet five core requirements: miniaturization, low power consumption, portability, real-time detection and anti-environmental interference. It can adapt to outdoor complex illumination, temperature and humidity working conditions, realize real-time acquisition, preprocessing, defect detection and result output of insulator hyperspectral data, and support independent operation at the edge without relying on cloud servers.

#### 2) Overall System Architecture

The device adopts an integrated architecture of "hardware acquisition + embedded computing + software processing". The hardware system is responsible for hyperspectral data acquisition, power supply and communication. The embedded computing platform is responsible for data preprocessing and defect detection inference. The software system realizes function scheduling, result display and data storage. Each module works collaboratively to realize end-to-end real-time detection.

#### 3) Performance Index Design

Combined with the engineering application scenario, the core performance indicators of the device are set:

The overall weight of the equipment $\leq 1$ kg, the whole machine power consumption $\leq 5$ W, the detection frame rate $\geq 15$ FPS, the defect recognition accuracy $\geq 90\%$, and it supports stable operation in the outdoor environment of $-10$ °C–50 °C, meeting the needs of portable inspection and real-time detection.

### B. HARDWARE SYSTEM DESIGN AND SELECTION

#### 1) Lightweight Hyperspectral Imaging Module

A small snapshot hyperspectral imaging module is selected, with a wavelength range of 450–950 nm and a spectral resolution of 5 nm. It has small volume and fast imaging speed, can complete real-time imaging without push-broom, adapts to the integration requirements of lightweight equipment, and can accurately capture the spectral characteristic changes of insulator defects.

#### 2) Selection of Embedded Computing Platform

The Rockchip RK3588 embedded computing platform is selected. This platform has moderate computing power, low power consumption and small volume, supports deep

TABLE 3. Parameter Table of Core Hardware Modules of the Device

| Hardware Module | Core Parameters | Power Consumption/W | Volume/mm |
|---|---|---|---|
| Hyperspectral Imaging Module | 450–950 nm, 5 nm resolution | 1.2 | 45 × 35 × 28 |
| Embedded Computing Platform | 6-core processor, 6 TOPS computing power | 2.5 | 82 × 55 × 15 |
| Power Supply Module | 12 V/5000 mAh | 0.8 | 60 × 40 × 20 |
| Communication Module | WiFi+Bluetooth dual mode | 0.3 | 30 × 25 × 8 |

learning model inference acceleration, can meet the needs of real-time processing of hyperspectral data and lightweight model inference, and is perfectly adapted to outdoor edge deployment scenarios.

#### 3) Design of Power Supply and Communication Modules

A large-capacity lithium battery power supply module is configured, supporting continuous battery life of more than 6 hours, meeting the demand for all-day field inspection.

It is equipped with a WiFi and Bluetooth dual-mode communication module, supporting local storage and wireless transmission of detection data, and can realize real-time upload and remote viewing of detection results.

The selection parameters of core hardware modules are shown in Table 3.

### C. SOFTWARE SYSTEM DEVELOPMENT

#### 1) Data Acquisition and Transmission Module

A real-time hyperspectral data acquisition program is developed to realize parameter configuration, image acquisition and data reading of the imaging module, and synchronously complete the real-time transmission of data to the computing platform, ensuring the continuity and stability of data acquisition and providing data support for subsequent processing.

#### 2) Real-Time Data Preprocessing Module

The preprocessing algorithm is lightweight transplanted to the embedded platform to realize real-time denoising, correction, normalization and band selection of hyperspectral data, eliminate invalid data and interference information, and improve the accuracy and speed of subsequent defect detection.

#### 3) Defect Detection Algorithm Deployment

The optimized lightweight detection model is deployed to the embedded platform through the inference engine, and model adaptation, operator optimization and inference acceleration are completed to realize real-time identification, positioning and classification of insulator defects, and synchronously output defect type and confidence information.

### D. LIGHTWEIGHT OPTIMIZATION OF DETECTION ALGORITHM

TABLE 4. Ablation Experiment Results of Lightweight Algorithm Optimization

| Experimental Group | Optimization Strategy | Model Volume/MB | Inference Speed/FPS | mAP@0.5/% |
|---|---|---|---|---|
| 1 | Original model | 89.6 | 4.2 | 93.2 |
| 2 | Pruning + Quantization | 13.2 | 18.6 | 90.5 |
| 3 | Pruning + Quantization + Knowledge Distillation | 13.2 | 18.2 | 92.8 |
| 4 | All optimization strategies | 13.2 | 22.5 | 92.8 |

#### 1) Model Pruning and Quantization

The structured pruning algorithm is used to eliminate redundant convolutional layers and parameters of the model and remove invalid weights. the INT8 quantization technology is used to compress the 32-bit floating-point parameters of the model into 8-bit integer parameters, which greatly reduces the model storage volume and computing power consumption. The compressed model volume is reduced by more than 85%.

#### 2) Knowledge Distillation Method

The knowledge distillation strategy is adopted, taking the high-precision original model as the teacher model and the lightweight model as the student model. The feature knowledge output by the teacher model is used to supervise the training of the student model, making up for the accuracy loss caused by pruning and quantization, and achieving the effect of "small model with high precision".

#### 3) Operator Fusion and Hardware Acceleration

The operators such as convolution, normalization and activation function of the model are fused and optimized to reduce the calculation frequency. adapt to the hardware characteristics of the embedded platform, turn on GPU hardware acceleration, greatly improve the model inference speed and ensure the real-time detection capability.

The ablation experiment results of the lightweight algorithm are shown in Table 4.

### E. DEVICE INTEGRATION AND DEBUGGING

#### 1) Hardware Integration and Joint Debugging

Complete the integrated assembly of each hardware module, optimize the equipment wiring and heat dissipation structure, and do a good job in dustproof and moistureproof protection of the equipment to adapt to outdoor working conditions.

Complete the joint debugging of hardware modules, detect the collaborative working stability of imaging, power supply, communication and computing modules, and solve the problem of module adaptation conflicts.

#### 2) Software System Testing

Conduct independent testing and overall joint debugging of each functional module of the software, verify the accuracy and stability of data acquisition, preprocessing, defect detection and data transmission functions, optimize the program operation logic, and fix problems such as program jamming, data loss and detection abnormality.

## V. EXPERIMENTAL VERIFICATION AND FIELD APPLICATION ANALYSIS

### A. EXPERIMENTAL ENVIRONMENT AND EVALUATION INDEXES

#### 1) Laboratory Experimental Environment

A standardized test platform is built in the laboratory, equipped with adjustable illumination, temperature and humidity control systems, and equipped with the self-developed lightweight detection device. The hyperspectral sample library of insulators constructed in this paper is used as the test dataset to complete the basic performance verification of the algorithm and device.

#### 2) Field Test Environment

The 110 kV and 220 kV conventional transmission lines in the region are selected as the field test scenarios, covering typical inspection environments such as suburbs, industrial areas and humid mountainous areas, including various weather conditions such as sunny days, cloudy days and weak light, to verify the field adaptability of the device.

#### 3) Performance Evaluation Indexes

In this paper, mean average precision at IoU=0.5 (mAP@0.5), detection frame rate (FPS), defect detection rate, false detection rate and equipment power consumption are taken as the core evaluation indexes to comprehensively evaluate the effectiveness of the sample library, algorithm accuracy, device real-time performance and stability.

### B. VALIDITY VERIFICATION EXPERIMENT OF THE SAMPLE LIBRARY

#### 1) Influence of Different Sample Libraries on Detection Accuracy

The same lightweight model is trained with the general hyperspectral dataset, the unaugmented original sample set and the standardized sample library after augmentation in this paper respectively, and the detection accuracy is compared.

The results show that the mAP@0.5 of the model trained with the sample library constructed in this paper is significantly better than that of other datasets, proving that the diversity and standardization of the sample library can effectively improve the detection accuracy and generalization ability of the model.

#### 2) Effect Comparison of Data Augmentation Methods

The effectiveness of the spectral-spatial joint augmentation method is verified through ablation experiments. The model using only spatial augmentation or spectral augmentation has limited generalization ability, while the joint augmentation method can effectively improve the model's ability to identify scarce defects and complex working conditions, and the overfitting phenomenon is significantly improved.

**TABLE 5.** Field Performance Comparison of Different Insulator Detection Methods

| Detection Method | Hidden Defect Detection Rate/% | False Detection Rate/% | Single Tower Detection Time/s | Equipment Portability |
|---|---|---|---|---|
| Manual Inspection | 35.2 | 12.5 | 120 | Excellent |
| Infrared Detection | 58.6 | 8.3 | 45 | Good |
| Visible Light Detection | 42.3 | 10.2 | 30 | Good |
| Self-developed Device in This Paper | 90.1 | 2.1 | 12 | Excellent |

#### 3) Cross-Environment Generalization Ability Test

The model trained in the laboratory is directly applied to field detection to test the cross-environment generalization performance of the model. The results show that the defect detection rate of the model trained based on the multi-working-condition sample library in this paper decreases slightly in the complex field environment, and its generalization ability is significantly better than that of the model trained with traditional single-working-condition samples.

### C. PERFORMANCE TEST OF LIGHTWEIGHT DETECTION DEVICE

#### 1) Detection Accuracy Test

Under standard laboratory working conditions, the comprehensive detection mAP@0.5 of the device for five typical defects of insulators reaches 92.8%, and the recognition accuracy of various defects exceeds 90%. Its ability to identify hidden defects such as micro-cracks and mild contamination is significantly better than that of traditional detection methods.

#### 2) Detection Speed and Real-Time Performance Test

The inference frame rate of the device on the embedded end is stable above 22 FPS, far exceeding the real-time detection threshold of 15 FPS. It can realize continuous and real-time detection of insulator defects and meet the efficiency requirements of field dynamic inspection.

#### 3) Power Consumption and Stability Test

The average power consumption of the whole device is 4.8 W, and it can work continuously for more than 6 hours under full charge, adapting to all-day field inspection operations. after long-term continuous operation test, the equipment has no jamming, no crash and no abnormal data, and has good operation stability.

#### 4) Comparative Analysis With Traditional Detection Methods

The self-developed device is compared with traditional manual inspection, infrared detection and visible light detection methods on site, and the comprehensive performance advantage is significant. The specific comparison results are shown in Table 5.

### D. FIELD APPLICATION TEST AND RESULT ANALYSIS

1) Field Test Scheme

Multiple transmission lines with different voltage levels and different environmental working conditions are selected to carry out field actual measurement. The self-developed lightweight device is used to complete the full-line insulator detection, and the detection results, environmental parameters and equipment operation status are recorded synchronously, which are compared with the manual review results to verify the actual application effect of the device.

2) Detection Results Under Different Working Conditions

Under conventional working conditions of sunny and cloudy days, the defect detection rate of the device is stable above 90%.

Under complex working conditions such as humidity and light haze, the detection rate decreases slightly but still remains above 87%, which is far superior to traditional detection technologies and has good environmental anti-interference ability.

3) Field Application Problems and Solutions

The field test found that under extreme working conditions of strong backlight, excessive imaging light will slightly interfere with the spectral accuracy, leading to missed detection of a small number of weak defects.

Aiming at this problem, the detection performance under extreme working conditions is effectively improved by optimizing the imaging exposure parameters and adding the backlight spectral correction algorithm, and the stability of the device is further enhanced.

## VI. CONCLUSION

This paper completes the research and development and application of the hyperspectral sample library construction and lightweight detection device for insulators, and has achieved good research results, but there is still room for optimization:

First, the scale of the sample library can be continuously expanded in the follow-up, and samples under special working conditions such as extreme weather and long-term aging can be added to further improve the full coverage of the sample library.

Second, the algorithm structure can be optimized to improve the recognition accuracy of weak defects under extremely complex working conditions.

Third, the device can be iteratively upgraded to integrate the UAV mounting interface to realize UAV automatic inspection operation, further improve the inspection efficiency and intelligent level, and provide more perfect technical support for the construction of the power grid intelligent inspection system.

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