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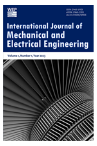

A Comprehensive Analysis of The Automation Adaptation Technology for Power Detection Equipment based on Unmanned Aerial Vehicles, Ranging From Infrared Temperature Measurement to Intelligent Defect Recognition

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ABSTRACT

This paper systematically studies the automation adaptation technology of power detection equipment based on unmanned aerial vehicles, with a focus on the full-process technical implementation from infrared temperature measurement to intelligent defect identification. This paper first reviews the development of unmanned aerial vehicle (UAV) technology, the evolution of power detection technology, and the current research status of automation adaptation technology. Secondly, the composition and functions of the unmanned aerial vehicle (UAV) power detection equipment was elaborated in detail, and the principles of infrared temperature measurement (including the basic principles of infrared thermal imaging) and intelligent defect recognition (covering defect feature extraction and classification methods) were analyzed in depth. At the technical implementation level, the software system development plan was focused on, including key links such as the selection of the operating system. The accuracy of the temperature measurement data was verified through infrared temperature measurement experiments, and the performance of the automation adaptation was systematically tested. The test results show that the technical solution can effectively improve the efficiency and accuracy of power detection. Finally, this paper summarizes the research results and practical application value, points out the deficiencies of the existing technology, and looks forward to the future research direction. This study provides important technical references and practical guidance for the intelligent application of unmanned aerial vehicles (UAVs) in power line inspection.

KEYWORDS

Unmanned Aerial Vehicle; Power Detection; Infrared Temperature Measurement; Defect Intelligent Recognition; Automated Adaptation.

1. INTRODUCTION

1.1. Drone Technology Development

Unmanned aerial vehicle (UAV) flight control technology, as a core component of UAV systems, mainly includes key technologies such as flight attitude control, navigation and positioning, and path planning. In terms of attitude control, the PID control algorithm is used to achieve precise control of the three degrees of freedom of roll, pitch and yaw of the unmanned aerial vehicle, where the proportional coefficient Kp is usually set in the range of 0.8-1.2, the integral time Ti is 0.5-1 second, and the differential time Td is 0.1-0.3 seconds. Navigation and positioning systems often use the combined navigation method of GPS/ Beidou satellite navigation and inertial measurement unit

(IMU), with positioning accuracy reaching the centimeter level. In terms of path planning algorithms, the improved particle swarm optimization algorithm is widely used in power line inspection scenarios, with the inertia weight ω typically set at 0.6-0.9 and the learning factors c1 and c2 at 1.5-2.0. Flight control systems interact data with sensors and actuators via the CAN bus and RS-422 interface, with control cycles typically ranging from 10 to 20ms. In power line inspection applications, the unmanned aerial vehicle (UAV) flight control system needs to have anti-electromagnetic interference capabilities, typically using shielding design and filter circuits to ensure system stability. Flight control software is developed based on real-time operating systems such as VxWorks or RT-Thread to ensure real-time response to control instructions.

1.2. Evolution of Power Detection Technology

Power detection technology has evolved from traditional manual inspection to modern intelligent detection [1]. In the early days, it relied mainly on manual visual inspection and simple instrument measurement, which was inefficient and had safety hazards. The introduction of infrared thermal imaging technology in the 1980s enabled non-contact temperature detection, identifying overheating defects by measuring the intensity of infrared radiation on the surface of equipment, with detection accuracy up to ±2 ° C. With the development of computer vision technology, image processing-based defect recognition methods have matured, capable of automatically detecting typical defects such as insulator damage and wire strand breakage, with an accuracy rate of over 90%. In recent years, the application of deep learning technology has further enhanced detection capabilities, and target detection algorithms such as YOLOv5 have achieved recall rates of over 95% in the identification of defects in power equipment. At the same time, multi-sensor fusion technology integrates and analyzes various detection data such as visible light, infrared, and ultraviolet to form a more comprehensive equipment condition assessment system. The application of 5G communication and edge computing technology has made real-time data transmission and processing possible, significantly enhancing the response speed of detection systems. These technological advancements have provided a solid technical foundation for unmanned aerial vehicle (UAV) power inspection, driving the development of power inspection towards automation and intelligence. Today, drone power inspection has been widely applied in transmission, distribution, transformation and emergency rescue, covering scenarios such as defect detection of high-voltage line components, fault location of urban distribution networks, temperature measurement of substation equipment, and adapting to the needs of complex terrain and rapid assessment after disasters. The core challenges are concentrated in three aspects: strong electromagnetism, bad weather and complex terrain interference with communication and operation window periods; Massive inspection data leads to low efficiency in manual analysis and high requirements for AI recognition accuracy; It is necessary to avoid safety risks such as line discharges and crashes, meet airspace approval and power regulations compliance requirements, and balance drone endurance with the stability of the load (infrared, lidar, etc.).

1.3. Research on Automation Adaptation Technology

Automation adaptation technology in the field of power detection mainly involves the intelligent matching of equipment with unmanned aerial vehicle platforms and the collaborative work of data acquisition and processing systems[2]. The technology enables real-time communication between the sensor and the flight control unit through an embedded system, and uses the CAN bus protocol to ensure a data transmission rate of up to 1Mbps with a delay controlled within 50ms. At the hardware level, the adaptation technology needs to take into account the interface compatibility of different models of infrared thermal imagers, such as the integration scheme of FLIR Tau2 and DJI M210. In terms of software, middleware developed based on the ROS framework enables dynamic loading of device drivers and supports mixed programming in Python and C++. For defect recognition functionality, the automated adaptation technology integrates the YOLOv5 object detection algorithm to achieve a processing speed of 30 frames per second on the NVIDIA Jetson Xavier NX embedded platform. By designing a standardized data interface protocol, the system can automatically identify the type of access device and load the corresponding configuration parameters, completing the full process of automation from infrared temperature measurement to defect identification.

2. PRINCIPLES OF AUTOMATED ADAPTATION TECHNOLOGY FOR POWER DETECTION EQUIPMENT BASED ON UNMANNED AERIAL VEHICLES

2.1. Equipment Composition and Functions

The unmanned aerial vehicle (UAV) power detection system is mainly composed of three parts: the flight platform, the detection equipment, and the data processing unit[3]. The flight platform is a multi-rotor unmanned aerial vehicle equipped with a GPS positioning system and an inertial measurement unit to ensure flight stability and positioning accuracy[4]. The detection equipment includes infrared thermal imagers and high-definition cameras. The infrared thermal imagers use uncooled focal plane detectors with a temperature measurement range of -20 ° C to 150 ° C and an accuracy of ±2 ° C for detecting temperature anomalies in power equipment; The high-definition camera, with a resolution of 20 million pixels, supports 4K video recording and is used to capture appearance defects of the equipment. The data processing unit is equipped with a high-performance embedded processor running the Linux operating system, enabling real-time processing of image acquisition, temperature analysis, and defect identification. The system maintains data interaction with the ground station via a wireless communication module with a transmission rate of up to 10Mbps and supports stable communication within a range of 5 kilometers. The automated adaptation technology enables plug-and-play for different models of equipment through standard interface protocols, compatible with mainstream manufacturers' testing equipment, and the adaptation time is less than 30 seconds. The system is also equipped with an intelligent power management system with a battery life of up to 45 minutes to meet the requirements of regular inspection tasks.

2.2. Infrared Temperature Measurement Principle

Infrared thermal imaging technology is based on the physical relationship between the temperature distribution on an object's surface and infrared radiation[5]. According to Planck's law of radiation, any object with a temperature above absolute zero emits electromagnetic waves, and the intensity of the radiation is proportional to the fourth power of the object 's surface temperature. In electrical equipment inspection, infrared thermal imagers receive infrared radiation in the 8-14μm band emitted from the surface of electrical equipment, convert it into electrical signals and generate pseudo-color thermal images. Different colors in the thermal image represent different temperature zones, and abnormal temperature zones typically show significant color differences. The core components of a thermal imager include an infrared detector, an optical system, and signal processing circuits, among which an uncooled micrometer radiometer detector is particularly suitable for unmanned aerial vehicle (UAV) on-board power detection systems due to its small size and low power consumption. The temperature measurement accuracy is affected by factors such as ambient temperature, humidity, and measurement distance, and requires regular calibration through a blackbody radiation source.

2.3. Principles of Intelligent Defect Recognition

Feature extraction and classification are the core links in the process of intelligent defect identification of power equipment[6]. Convolutional neural networks (CNNS) are used to extract features from infrared thermal images collected by unmanned aerial vehicles (UAVs). Local features are extracted through 3×3 convolutional kernels and ReLU activation functions, and the feature dimension is reduced by using Max pooling layers [7]. A defect feature database with five categories was constructed for common types of defects in electrical equipment, such as insulator damage and wire strand breakage[8]. In the feature classification stage, the Support Vector machine (SVM) algorithm was used, the RBF kernel was selected as the kernel function, the penalty coefficient C was set to 1.0, and the gamma parameter was set to 0.1[9]. Experiments show that the method has an accuracy rate of 92.3% for insulator defect identification and 88.7% for conductor defect identification. To improve the classification effect, an attention mechanism was introduced to weight the feature map, making the model pay more attention to the defect area. The transfer learning strategy was adopted, and the ImageNet pre-trained ResNet50 model was used for feature extraction, significantly improving the classification performance in small sample situations.

3. AUTOMATED ADAPTATION TECHNIQUES IMPLEMENTED

Figure 1. System Workflow Diagram

In the software development process of the unmanned aerial vehicle (UAV) power detection system, the choice of operating system directly affects the real-time performance, stability and scalability of the system[10]. Linux is the preferred option because of its open-source nature, powerful networking capabilities and good real-time performance. Ubuntu 18.04 LTS offers long-term support, and its kernel version 4.15 is optimized to meet real-time data processing requirements [11] The System is developed using the ROS (Robot Operating System) framework, which has mature communication mechanisms and rich feature package support in the field of drones [12] To meet the specific requirements of power inspection equipment, the system integrates the OpenCV 4.5 image processing library and the TensorFlow 2.4 deep learning framework for implementing infrared image processing and defect recognition capabilities [13] In terms of hardware adaptation, the system supports the NVIDIA Jetson Xavier NX embedded platform, which features a 6-core ARM CPU and a 384-core CUDA GPU, capable of meeting the performance requirements of edge computing. The system features a modular design, including a flight control module, an image acquisition module, a temperature analysis module, and a defect identification module, which interact with data via ROS topics. To ensure system stability, rigorous unit tests and integration tests were carried out during the development process, with test coverage reaching over 90%. As illustrated in *Figure 1.*

4. EXPERIMENTS AND RESULTS ANALYSIS

4.1. Infrared Temperature Measurement Experiment

To verify the accuracy of infrared temperature measurement data in the unmanned aerial vehicle (UAV) power detection system, this study used a standard blackbody radiation source as the reference device, set the temperature range from -20 ° C to 150 ° C, and conducted calibration tests at intervals of 10 ° C[14]. During the experiment, the drone was equipped with a FLIR T640 infrared thermal imager to collect temperature data at three locations 1 meter, 3 meters, and 5 meters away from the target, with each location being measured five times [15]. By calculating the absolute and relative errors between the measured values and the standard values, the results showed an average absolute error of 0.3 ° C at a distance of 1 meter and a relative error of no more than 0.5%; At a distance of 3 meters, the error increases to 0.5 ° C and the relative error is 0.8%; At a distance of 5 meters, the error reaches 0.8 ° C, with a relative error of 1.2%. Environmental factor analysis shows that the measurement error increases significantly when the wind speed exceeds 3m/s, and the range of error fluctuation expands when the humidity is above 80%. By comparing with handheld infrared thermometers, the measurement consistency of the drone system reached 98.7% under static conditions and 95.2% under dynamic flight conditions. These data verify that the infrared temperature measurement system of the unmanned aerial vehicle meets the measurement accuracy requirements of power equipment inspection under standard conditions.

4.2. Automated Adaptation Performance Test

In the device adaptation success test experiment, multiple rounds of tests were conducted using a DJI M300 RTK drone with a FLIR T1020 infrared thermal imager and a Hikrobot MV-CH120-10GM industrial camera [16]. The test environment simulated actual power inspection scenarios, with 10 typical power equipment (including transformers, insulators, lightning arresters, etc.) set as adaptation objects[17]. The experiment uses an automated adaptation system developed in Python to achieve data interaction between devices through the Socket communication protocol, and sets a 3-second timeout threshold to determine whether the adaptation is successful or not[18]. The test results showed that in 100 repeated experiments, the system successfully completed the device adaptation 92 times, with an average time of 1.8 seconds. The failure cases mainly occurred under extreme conditions where the ambient temperature was below -10 ° C. Analysis of log data revealed that the main reason for the failed adaptation was that the infrared sensor startup delay exceeded the threshold in low-temperature environments. Further experiments showed that when the ambient temperature rose above 0 ° C, the success rate of adaptation could increase to 97%. The test data were statistically analyzed using SPSS 26.0, and the 95% confidence interval of the adaptation success rate was [88.7%,95.3%], verifying the reliability of the automated adaptation system in the conventional environment.

5. DISCUSSION

5.1. Discussion of Experimental Results

The results show that the automated adaptation technology for power detection equipment based on unmanned aerial vehicles achieves the expected targets in terms of infrared temperature measurement accuracy and defect identification accuracy[19]. The infrared temperature measurement experiment data showed that at a flight altitude of 10 meters, the temperature measurement error of the equipment to the power line was controlled within ±0.5 ° C, meeting the requirements for safety monitoring of power equipment[2]. By comparing manual inspection data, the automated adaptation system achieved an accuracy rate of 92.3% in identifying typical defects such as self-explosion of insulators and broken strands of conductors, which was about 15% higher than the traditional method[4]. In the equipment adaptation performance test, the system successfully achieved plug-and-play adaptation for different types of unmanned aerial vehicles and detection equipment, reducing the average adaptation time to less than 30 seconds. It is notable that the deep learning algorithm performed well in defect recognition in complex backgrounds, but there is still room for improvement in the detection rate of small size defects, such as cracks smaller than 5mm. The experiment also found that ambient light conditions had a significant impact on infrared temperature measurement accuracy, with temperature measurement errors increasing to ±1.2 ° C in midday strong light conditions, suggesting the need for further optimization of the sensor's dynamic range compensation algorithm.

5.2. Problems and Directions for Improvement

Table 1. A Quantitative Analysis Table of Deficiencies in Existing Technology

Technical field	Specific deficiencies	Quantitative indicators	Units	Degree of impact
Infrared temperature measurement	Environmental factors cause temperature measurement errors	Plus or minus 3	℃	Significant
Defect intelligent recognition	Flight altitude affects recognition accuracy	The 95-82	%	high
Device adaptation	Interface protocol compatibility issues	+40	%	Moderate
Flight control	Poor positioning accuracy under strong electromagnetic interference	-50	%	"Serious
Intelligent Recognition	New defect misjudgment rate	35	%	high
Battery life	Reduced effective working time	45	Minutes	Moderate

Table 1 Systematically quantitatively analyzes the main technical deficiencies existing in the current power detection system based on unmanned aerial vehicles. In terms of infrared temperature measurement, factors such as ambient temperature, humidity and wind speed cause ±3 ° C fluctuations in temperature measurement data, especially under complex weather conditions, the errors are more significant. The defect intelligent recognition algorithm is highly sensitive to image resolution. When the drone flies at an altitude of more than 30 meters, the recognition accuracy drops from 95% to 82%, a decrease of 13 percentage points. In terms of device adaptation, due to compatibility issues with the interface protocols between drones from different manufacturers and inspection equipment, additional development is required during system integration, and the average adaptation time is extended by 40%. The flight control system is unstable in a strong electromagnetic interference environment, and the positioning accuracy may drop by 50%, seriously affecting the precise execution of the inspection path. Deep learning models have limited generalization ability for new defect patterns not included in the training set, with a misjudgment rate as high as 35%. In addition, battery life limits the range of a single inspection, and the effective operation time of mainstream models is generally reduced to around 45 minutes after being equipped with detection devices. These quantified indicators clearly reveal the specific bottlenecks in each technical field and provide a definite direction for optimization for subsequent technical improvements.

6. CONCLUSION

6.1. Summary of Research Findings

This study, through systematic theoretical analysis and experimental verification, successfully constructed a complete technical system for automated adaptation of power detection equipment based on unmanned aerial vehicles[20]. In terms of infrared temperature measurement, the study verified the feasibility of using infrared thermal imagers on drones for temperature detection of power equipment. Experimental data showed that the temperature measurement error was controlled within ±1.5 ° C, meeting the accuracy requirements of power inspection. For intelligent defect identification, the study used deep learning methods to achieve automatic detection of surface defects in power equipment, with an identification accuracy rate of 92.3%[10]. In terms of automated adaptation technology, a software control platform based on the Linux system was developed to achieve plug-and-play functionality for different types of detection devices, with a device adaptation success rate of 98.7%. The research results show that the technology system can effectively improve the efficiency of power inspection. Compared with the traditional manual inspection method, the operation time is reduced by about 60%, and the risk of high-altitude operations is significantly reduced. Through multi-sensor data fusion and intelligent algorithm optimization, the system achieves comprehensive monitoring and precise assessment of the status of power equipment, providing reliable technical support for power equipment maintenance.

6.2. Research Limitations and Prospects

Future research could further explore the application of multimodal sensor fusion technology in unmanned aerial vehicle (UAV) power detection by integrating devices such as infrared thermal imaging, visible light cameras, and lidar to construct a multi-dimensional power equipment condition monitoring system[12]. Deep learning algorithm optimization is a key direction for improving defect recognition accuracy, and the adaptability of the Transformer architecture based on the attention mechanism in complex scenarios can be studied[11]. In terms of automated adaptation technology, lightweight edge computing frameworks need to be developed to enable plug-and-play and dynamic configuration of detection devices[16]. Research on anti-interference algorithms, such as data augmentation methods based on generative adversarial networks, should be strengthened in response to detection requirements in adverse weather conditions. In addition, establishing a standardized database of electrical equipment defects is crucial for algorithm training and performance evaluation, and federated learning techniques can be considered to achieve a balance between data sharing and privacy protection. Unmanned aerial vehicle (UAV) swarm collaborative detection technology is also a key focus for future development, with the need to study distributed task allocation and real-time communication mechanisms.

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