Current Status and Analysis of Key Technological Applications of Multi-Rotor UAV in High Voltage Cable Inspection

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Abstract. As the core link of power transmission, the safety operation and maintenance of high-voltage cables face the challenges of low efficiency and high risk of traditional manual inspection. This paper systematically analyze the key technologies of multi-rotor UAVs in high-voltage cable inspection, including multi-sensor fusion localization, path planning algorithm optimization, anti-jamming control, and data processing technology, and discuss the range enhancement strategy. The results demonstrate that the multi-sensor cooperative technology, integrating the improved potential field method, genetic algorithm, and deep learning, significantly enhances inspection accuracy and efficiency. However, dynamic obstacle avoidance in complex environments, insufficient range, and real-time data processing remain challenges. In the future, it is necessary to further optimize the robustness of the algorithm, explore new energy technology and cloud data analysis technology to achieve the comprehensive application of UAV inspection technology. It can be seen that the drone is not only a tool of innovation for high-voltage cable inspection, but also a key node in the digital transformation of the power system.

INTRODUCTION

Nowadays, China's rapid economic development, social power consumption have increased dramatically, and high-voltage cables play an important role in power transmission. Long-term exposure of high-voltage cables to natural environments leads to various faults, such as cable body damage, joint failures, high-voltage cable grounding system faults, high-voltage cable resistance faults. For fault inspection, traditional manual inspection is difficult, time-consuming and inefficient. The use of multi-rotor UAV inspection has a strong mobility, flexibility and stability can be a perfect solution to the shortcomings of manual inspection.

To improve the efficiency of high-voltage cable inspection, researchers have carried out many studies to optimize the path planning and obstacle avoidance ability of UAVs. Jiang and other scholars have improved the potential field method, genetic algorithm and RRT forest algorithm used for multi-rotor UAV path planning and obstacle avoidance, and these optimizations improve the success rate of dynamic scene obstacle avoidance during inspection by 40%, and shorten the path planning time in the dense cable area by 30%, which greatly improves the efficiency of the UAV in the inspection of high-voltage cables [1-4]. Yang et al. use hierarchical signal processing and adaptive power regulation to reduce noise from 13.70 Hz to 2.66 Hz so that unmanned aerial vehicles (UAVs) can still operate safely under strong electromagnetism [5]. As mentioned above, although UAVs have achieved certain results in path planning and static obstacle avoidance during high-voltage cable inspection, there are technical bottlenecks in endurance, dynamic obstacle avoidance and data processing.

This paper summarizes the sensors used in the positioning and obstacle avoidance technology of UAVs, and describes the current status of key technology applications of multi-rotor UAVs in high-voltage cable inspection, and analyzes the technical deficiencies to provide direction for future development.

Sensors And Navigation And Positioning Technology

Optical Sensors: Optical sensors are divided into photoelectric sensors, fiber optic sensors, image sensors and so on. The binocular camera or CCD camera in the image sensor can be used to recognize defects such as breakage of cable skin, surface foreign matter, insulator breakage, etc. through its high-resolution imaging capability. Static and dynamic targets can also be detected, tracked and localized. For example, the combination of Synthetic Aperture Radar (SAR) and CCD camera work in tandem, with the SAR responsible for wide-range moving target tracking and the CCD camera providing high-resolution images to assist in feature extraction. It also utilizes visual SLAM to locate in places not covered by GPS, such as cable-heavy areas and tall houses, and is suitable for close inspection in complex terrain [6, 7].

Lidar Sensors: Lidar sensors usually utilize pulse, phase, interferometric and triangulation methods for ranging to determine the altitude at which the UAV is flying. Through the point cloud generated by LiDAR and combined with Cartographer algorithm to realize LiDAR SLAM, the distance between the cable and the surrounding obstacles is monitored in real time to ensure the safety of UAV flight. And the LiDAR can work at night, making up for the limitations of optical sensors [8].

Ultrasonic Sensor: The working principle of ultrasonic sensors is based on the reflection characteristics of sound waves, four ultrasonic sensors are installed at the front, back, left and right sides of the UAV, and a single-axis stabilized gimbal is used to decouple the coupling between the detection direction and the attitude of the fuselage caused by tilting the fuselage during the flight of the multi-rotor UAV. Then the UAV can be stabilized to avoid obstacles when it is about to hit an obstacle. Combined with the Kalman filter to reduce the interference caused by noise, the reliability of obstacle avoidance is enhanced [8].

Infrared Sensors: Infrared sensors can monitor the temperature of the surface of high-voltage cables in real time by capturing the infrared radiation on the surface of the object, and quickly identify the part with abnormal temperature. The infrared weak target detection method based on deep U-network can optimize the recognition ability of tiny targets in infrared images to monitor the tiny damage on the cable surface [9].

PATH PLANNING ALGORITHMS

Potential Field Method

The potential field method is to model the UAV movement environment as a virtual potential field, and use the force generated by the attraction and repulsion potential fields to carry out UAV path planning. Firstly, the corresponding threat potential functions are constructed for different threat sources, the obstacles in the complex environment are simplified into circular regions, and the connectivity of these regions is analyzed using geometric topology ideas to determine the feasible solution domain. The initial paths are generated through the preplanning of trajectory points, and then combined with the full situation field information to avoid the stagnation of the paths caused by the lack of local information in the traditional potential field method [10]. With YOLOv5s target detection algorithm to identify the pixel position of the obstacle in real time, combined with the stereo matching algorithm of the binocular camera to obtain the three-dimensional coordinate information of the obstacle, to ensure the accurate positioning of the dynamic obstacle. It is also necessary to set the gravitational threshold to limit the gravitational strength of long-distance targets to avoid the failure of obstacle avoidance due to excessive gravitational force [1]. Using the improved potential field method and through global pre-planning guidance, local potential field optimization and path smoothing constraints, Ding and other scholars effectively overcome the inherent defects of the traditional APF and show stronger robustness, adaptability and practicality in complex environments, which provides an efficient and reliable solution for UAV path planning [10].

Genetic Algorithm

Genetic algorithm is a kind of bionic optimization algorithm simulating the biological evolution process, which searches for the optimal solution of the problem in the solution space by simulating the mechanisms of natural selection, gene crossover and mutation. Under the basis of traditional genetic algorithm, Jiang and other scholars can significantly improve the efficiency of path planning by optimizing the selection, crossover and mutation operators of genetic algorithm and combining with the three times B-spline curve to smooth the path. Firstly, an environment model containing terrain and obstacles is established to simulate the complexity of the real scene, and then into the comprehensive consideration of voyage cost, terrain cost and boundary constraints, to establish the optimization model line that minimizes the total cost. Compared with the traditional GA, the improved algorithm reduces the generation value by 68% and the number of convergence iterations by 67%. It facilitates the analysis of cables distributed in complex areas to quickly locate passable paths, and ensures smooth UAV flight trajectories through three times B-spline curve smoothing [2]. The algorithm is significantly better than the traditional method in convergence speed, path quality and environment adaptability through the collaborative improvement of multiple operators and path post-processing optimization, providing an efficient and reliable solution for UAV path planning in complex scenes.

RRT Forest Algorithm

The RRT forest algorithm is a path planning method designed for complex dynamic environments, and its core idea is to improve the efficiency and success rate of path search by generating multiple "random trees" at the same time. The traditional RRT algorithm gradually expands a tree by random sampling to find a path, but in complex or dynamic scenarios, it is easy to fail due to the limited search range of a single tree, while the RRT forest algorithm covers a wider area by expanding multiple trees in parallel, with each tree growing from a different location or direction, which improves the operational efficiency by about 25% compared to the traditional single-tree RRT algorithm [11]. The algorithm comprehensively improves the operational efficiency, safety and sustainability of UAVs in complex landscapes through a combination of environment modeling, dynamic adjustment and optimization techniques.

HC-SAR Novel Algorithms

Currently, some new hybrid optimization algorithms show advantages in UAV path optimization. The HC-SAR algorithm proposed by Guangxi University for Nationalities and Guangxi Key Laboratory of Hybrid Computing and Integrated Circuit Design and Analysis combines the Squirrel Algorithm (SAR) and heuristic crossover strategy with individual optimization. The team demonstrated through 2D and 3D test environment experiments that the algorithm has significant advantages in terms of path length, convergence speed, stability and reliability. Hybrid optimization algorithms have more potential for UAV path algorithm planning [12].

ANTI-INTERFERENCE CONTROL

In Yang et al.'s study, electromagnetic interference is classified into four levels, and the interference strength is dynamically determined by calculating the interference margin Δ. Δis derived from parameters such as signal-to-noise ratio and interference frequency, and is used to trigger different response strategies.

$$\Delta = S_j - P_s = P_n R_{SNs} R_{ISj} - P_n R_{SNs} \tag{1}$$

where Δinterference margin;S_j out-of-lock effect threshold;P_s interfering signal power;P_n frequency of the nth signal detected;R_{SNs} signal-to-noise ratio of the original signal;R_{ISj} D-effect interference signal-to-noise ratio of the interfering signal j. According to the interference level, the Longley-Rice model is used to predict the signal attenuation, and the ground transmit power P_t is dynamically adjusted to ensure the downlink signal strength and guarantee the complete data transmission.

$$P_t = P_s + E - (G_r + G_t) \tag{2}$$

where E signal attenuation coefficient; G_r receive antenna gain; G_t transmit antenna gain. Then the high-frequency alternating electromagnetic noise from the airborne receiver is subjected to three-layer wavelet decomposition. The first layer of high-frequency wavelet coefficients is cleared by the hard thresholding method, and the subsequent decomposition layers are processed by the soft thresholding method to smooth the noise signal. For the equivalent current electromagnetic noise, a Cohen-like time-frequency distribution kernel function is used to analyze the noise energy distribution and extract the time-domain ridge features. The compensation model is established by one-dimensional linear regression, and the compensation coefficients a and b are optimized to be used to correct the signal and offset the magnetic field interference [13]. This method reduces the noise from 13.70Hz to 2.66Hz and the original signal as a whole will be within the safety line, providing a reliable technical solution for the safe operation of UAVs in a strong electromagnetic environment.

CONTINUITY TECHNOLOGY

The length of high voltage cable is long, which puts higher requirements on the range of the UAV. Multi-rotor UAV range is affected by the overall aircraft quality, battery parameters, and flight algorithms. Some scholars, through modeling estimation and other methods, found that the selection of appropriate UAV flight control, structural design, power system optimization, flight control algorithm optimization, etc. can significantly improve the endurance of multi-rotor UAVs [14]. According to Stephen Andrew Wilkerson P.E, it is possible to first analyze the lift-to-drag ratio and Reynolds number of different airfoil configurations using Airfoil Tools, and then combine this with 3D printing technology to manufacture custom propellers and optimize the manufacturing constraints through composite materials. Second, Excel tools are developed to evaluate the thrust, current and weight of motor-propeller combinations to screen for efficient lightweight solutions, while MATLAB programs are used to analyze thrust requirements and flight time for multi-rotor configurations. It is expected to be able to improve the Guinness World Record of 2 hours, 14 minutes and 23 seconds for a 5-20 kilogram class UAV to 2 hours, 57 minutes, breaking the 42-minute mark [2].

DISCUSSION AND ANALYSIS

This paper systematically explores the key technologies of multi-rotor UAV in high-voltage cable inspection, and the research results show that the combination of multi-sensor fusion and improved path planning algorithm significantly improves the accuracy and efficiency of inspection. For example, the improved potential field method effectively solves the local stagnation problem of the traditional potential field method through the combination of full potential field information and dynamic obstacle localization; the genetic algorithm combines the path smoothing processing of the cubic B-spline curves to achieve an efficient and safe flight trajectory in complex terrain; the RRT forest algorithm enhances the success rate of path searching in dynamic environments through the parallel expansion strategy of multi-trees; and the HC-SAR novel algorithm combines the heuristic crossover strategy with the base SAR to improve the path length, convergence speed and stability. In addition, the multi-sensor synergistic technology realizes complementary advantages in different scenarios, which enhances the UAV's ability to detect cable defects and environmental adaptability.

However, there are still many problems that need to be solved, such as insufficient adaptability to complex environments, still relying on preset algorithms for dynamic obstacle avoidance, and lack of autonomous decision-making ability for unexpected events. Restricted range, although the range has been improved, factors such as low battery energy density and high altitude wind resistance still restrict long-time inspection tasks. Data processing and transmission bottlenecks, the massive data generated by the combination of multiple sensors has high requirements for onboard computing resources, and a more complete processing program is needed.

So the future research can be carried out in the following directions. Algorithm robustness optimization, in Zhu and other scholars' research by improving the PSO algorithm combined with the IPSO-CHNN model, the use of CHNN's energy function minimization characteristics, and through the PSO optimization of the CHNN's global search ability, which significantly improves the robustness and efficiency of the UAV path planning [5]. This research provides a new hybrid algorithmic framework for UAV path optimization and lays the foundation for future algorithmic optimization. Integration of new energy technologies, with hydrogen-powered UAVs as an important development direction for new energy-powered vehicles, has become a key technology for realizing the goals of green aviation and low-altitude economy by virtue of the high-quality energy density and zero-carbon emission characteristics of hydrogen fuel. The current technical challenges are mainly focused on the improvement of hydrogen storage efficiency, multidisciplinary collaborative design and intelligent upgrading. In the future, through interdisciplinary collaboration and technological iteration, hydrogen-powered UAVs are expected to realize breakthroughs in endurance, environmental adaptability and mission diversity [12]. Edge cloud collaborative computing, sinking computing resources to the edge of the network, deploying detection algorithms based on convolutional neural networks, supporting real-time processing and local data storage, reducing dependence on the central cloud, and deploying local 5G base stations to realize real-time transmission of image data [13]. The synergistic application of 5G and edge cloud provides an efficient and reliable solution for UAVs on high voltage cable inspection.

CONCLUSION

Multi-rotor UAVs are gradually replacing traditional manual methods in the field of high-voltage cable inspection, and their core advantages are reflected in high efficiency, flexibility and safety. In the current technology system, the multi-sensor cooperative positioning technology realizes accurate navigation under complex terrain and rapid identification of cable surface defects through the combination of visual imaging and laser scanning. Lidar combined with optical sensors allows the UAV to work at night. Dynamic algorithms based on global environment modeling optimize the limitations of traditional methods, for example, by bionic optimization strategy to improve the efficiency of path search, combined with smoothing processing technology to ensure the stability and safety of the flight trajectory, which significantly enhances the real-time response capability to dynamic obstacles. For the electromagnetic interference problem, the application of layered signal processing and adaptive power regulation technology effectively reduces the noise interference and ensures the reliability of communication in the complex electromagnetic environment. In terms of range enhancement, lightweight materials and power system optimization extend the flight time, and the selection of appropriate UAV flight control, structural design, power system optimization, and flight control algorithm optimization can significantly improve the range of multi-rotor UAVs, but high-altitude wind resistance and energy management are still the main constraints at present.

The main bottlenecks lie in the lack of autonomous obstacle avoidance capability in complex scenarios, the pressure of real-time processing of multi-source data and the range bottleneck. The future development direction needs to focus on the in-depth optimization of intelligent algorithms, promote the practical application of new energy power systems, combine edge computing and high-speed communication technologies to improve data processing efficiency, and enhance the environmental adaptability and mission scalability of UAVs through cross-domain technology integration. Overall, multi-rotor UAVs have begun to play an important role in high-voltage cable inspection, but systematic breakthroughs in algorithms, energy and data link bottlenecks are needed to promote the technology to a comprehensive intelligent and sustainable direction.

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