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Integrating Intelligent Sensors for Safe UAV Distribution: Design and Evaluation of Ranging System

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Abstract

In our increasingly electrified society, electricity has become indispensable to both production and daily life. However, high-load electric energy transmission presents inherent safety risks. To ensure the secure transportation of electric energy, live work on distribution networks is essential. However, traditional live work techniques require a high level of dependence on worker experience, which frequently leads to inaccurate safety distances and degrades worker security. This study proposes the integration of Unmanned Aerial Vehicles (UAVs) with intelligent robot sensing technology to enhance safety and efficiency in live work. By accurately measuring safety distances, UAVs offer a promising solution to mitigate risks associated with high-voltage circuits. Comparative analysis between traditional and intelligent live work safety distance measurements reveals the two live works under the high voltage circuit were 92% and 96%, respectively, and the accuracy of the two live work safe distance measurements under the low voltage circuit was 84% and 99%, respectively. Results demonstrate that UAVs equipped with intelligent sensing technology achieve superior accuracy in safe ranging for live work, thereby ensuring stable energy transmission and safeguarding the lives of workers in distribution networks.

Keywords: Safe Ranging; Distribution Network Live Work; Drone Ranging; Intelligent Robot Sensing Technology.

1. Introduction

Electricity was invented and used in industrial production beginning in the 1870s. The advancement of electricity has improved every household's standard of living. On the other hand, as social and economic conditions have improved, the amount of electricity consumed in homes and businesses has increased significantly, and as a result, there is a growing demand for electrical energy. Although the distribution network's live operation is a very risky precaution against power outages, it is an effective one. To lower the risk of live work, relevant researchers have measured safe distances for the distribution network's live operations. Among them, the observation that maintaining a specific safety distance from high-voltage equipment is imperative since working on the distribution network in real-time is extremely risky [1]. During the live distribution network, construction workers should maintain a safe distance of more than 40 cm [2]. The distribution system for AC station equipment with varying voltage levels has a variable electrified distance. The recommended safety distance increases with voltage [3]. In high-altitude regions, the safe distance between 3000 and 5000 meters above sea level is tested for live work on household lines [4]. When evaluating the safety distances of

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ground equipment and voltage equipment at various distances, he found that there are differences in the safety distances under various discharge gaps [5]. Construction workers' safety can be efficiently ensured by maintaining the safety distance during live work in a reasonable manner; however, the safety distance is not measured intelligently enough.

Accurate distance measurement is a feature of the intelligent sensing equipment on the UAV, and it is used to measure the safe distance between live distribution network operations. Among them, using intelligent drones to measure the safe distance for live work can effectively increase the accuracy of safe distance computation [6]. The UVA combined with intelligent robot sensing technology can determine the safe distance by using sensing equipment to thoroughly assess variables like voltage, altitude, and air humidity of high-voltage equipment [7]. UAVs have a high sensitivity, and using them to safely monitor high-voltage equipment can increase live work efficiency [8]. The safety range of live work may be precisely measured by Borah S using intelligent UAV technology, hence improving worker safety [9]. The techniques employed are subpar, even though UAVs with intelligent robot sensing technologies can reliably determine the safe distance for live work. Sensors are used by intelligent robot sensing technology to collect data. To determine the safe distance of live work in distribution networks, intelligent factor analysis and intelligent robot sensing technologies can be applied to UAVs [10]. The primary goal is to improve safety and efficiency in live distribution network work by combining Unmanned Aerial Vehicles (UAVs) with intelligent sensing technologies to precisely estimate safety distances, thereby reducing risks associated with high-voltage circuits.

For a variety of electrical line maintenance tasks, a single-arm live operating robot was established by Gu et al. [11]. A technique of automated terminal reconfiguration on transmission lines is also provided to achieve transmission line inspections with live operation automatically. For the standard fitting's maintenance operation, the robot's physical model and the manipulator arm's motion planning are provided. A design plan for an automated offline and online system for a live, functional robot was presented by Zou et al. [12]. The study develops a fundamental configuration and physical method, examines the principles of robots offline and online, and proposes a motion plan for operations. The viability and efficacy of the system are confirmed as a tangible prototype was generated. A conceptual and operational approach for an autonomous double-arm live working robot's on-line and off-loading mechanism was proposed in Zou et al. [13] and depends on UAV support. The structure of the lifting hook and the additional hook of the down and up system were built after the autonomous up-and-down process of the robot was investigated. After that, the robot's up-and-down force analysis was performed, and a theoretical calculation was used to determine that hook drive motor would be best. A double-arm collaborative robot's fundamental configuration was suggested by Quan et al. [14]. Polynomial interpolation theory was used to plan the trajectory of the robot arm motion simultaneously. The robot manipulator's trajectory planning simulation framework was constructed in the framework of MATLAB, and the robot manipulator's reconstruction of the end tool and its transportation to the work point are the subjects of the trajectory simulation research. An automated online system for repairing overhead transmission wires was developed by Zhao et al. [15]. The walking structure and pre-twisted cable winding structure should be part of the mechanical system that the ground wire repair device for overhead power lines is built and researched for initially. The operating system of the device, reception modules, data transmission, image transmission, and other associated hardware and software control systems need then be developed. Lastly, other wireless terminal control systems, comparable control equipment, and software for mobile phones should be produced.

2. Method of Safe Distance Measurement for Live Work in Distribution Network

The development of a social economy is inseparable from the supply of electric energy. Due to the increasing demand for electric energy, the power system is often overloaded, resulting in power supply failures [16-17]. It is essential to takeaway live work on the distribution network to ensure the continuous supply of electric energy, but live work is very dangerous. High-voltage electricity would cause serious injury or even death to construction personnel within a certain range. It is also necessary to maintain a safe distance during the live distribution network process. The structural model of the live distribution network operation is shown in Figure 1.

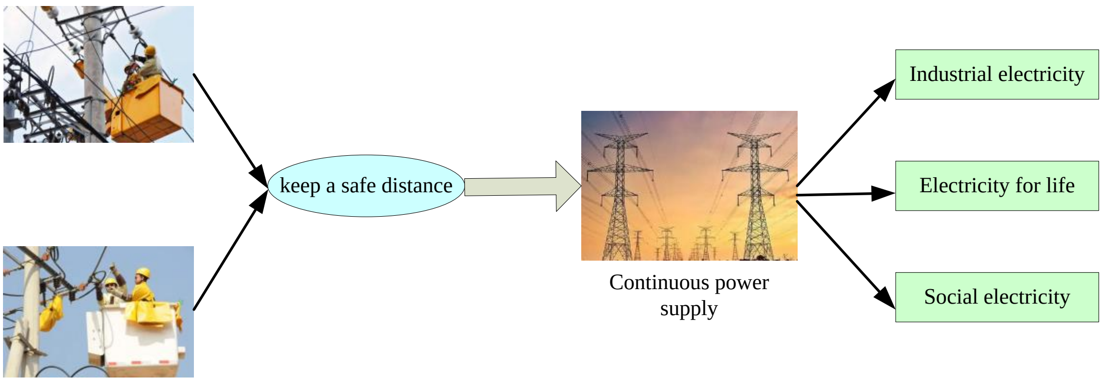


Figure 1. Structure model schematic of the distribution network's live work

In Figure 1, during the live work of the distribution network, the construction personnel need to keep a certain safety distance, which can not only ensure the safety of the construction personnel but also ensure the continuous supply of electric energy [18]. The live work of the distribution network provides stable electric energy for social development, industrial production, and people's lives.

3. Distribution Network Live Work

Reducing the duration of circuit breakdown during maintenance and maintaining a steady power supply are the goals of the distribution network's live operation. In the process of live work of the distribution network, the main and most frequently used work content is wiring. The power supply of the maintenance party's circuit is not affected by the wiring operation [19]. The lead model for the distribution network's live work is displayed in Figure 2.

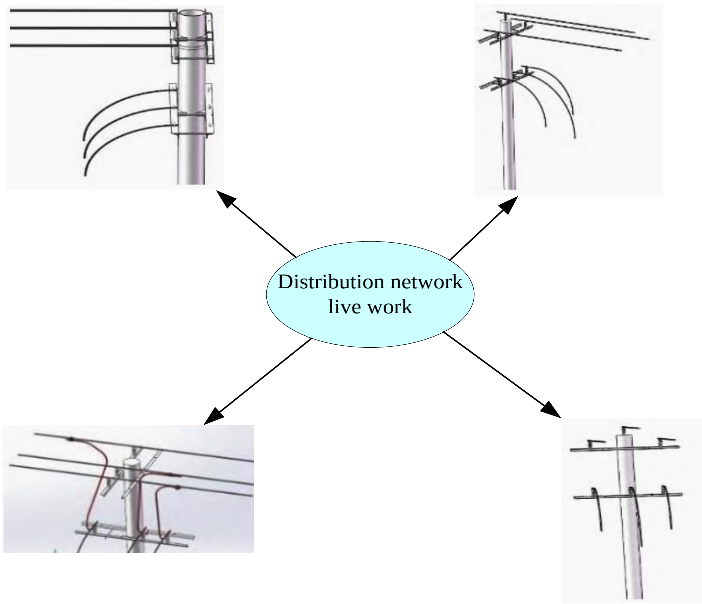


Figure 2. Model diagram of wiring connection for live work of distribution network

In Figure 2, the lead wires for live work in the distribution network are divided into four structures, namely horizontal lead, vertical lead, triangular horizontal lead, and triangular vertical lead [20]. The construction personnel choose different connection methods according to the different conditions of the maintenance circuit. The live work of the distribution network is a high-altitude operation; the construction environment is poor, and there is a danger of high-voltage electric shock. Additionally, essential is the distribution network's ongoing work. When working on a live distribution network, construction workers must prioritize their safety.

4. Safe Distance for Live Work in a Distribution Network

The safety distance for live work in the distribution network refers to the distance between construction personnel and high-voltage equipment. A certain safety distance is maintained to effectively protect the personal safety of construction workers. Based on their experience, the construction workers often maintain a safe distance while the live operation of the distribution network. Due to the different dangers in different voltage environments, it is an unsafe behavior for construction personnel to repair only based on experience [21]. Table 1 displays the safety distances at various circuit voltages.

Table 1. Safety distance table under different circuit voltages

Circuit voltage (kv)	Voltage level	Safe distance (m)
<10	1	0.7
30	2	0.8
100	3	1.5
220	4	3.0
500	5	5.2
800	6	8.5
1000	7	9.5

The voltage of the distribution network's live operation is broken down into 7 levels in Table 1. When the circuit voltage is less than 10kv, a safety distance of 0.7 meters should be maintained. The higher the circuit voltage, the longer the safe distance should be maintained, and the higher the difficulty and danger to the construction. When the circuit voltage reaches 1000kv, a safety distance of 9.5 meters should be maintained.

The safety distance mentioned above is measured in a standard environment, but the actual live working environments of distribution networks are different, and it is necessary to comprehensively analyze the safety distance of live working [22].

5. Intelligent Robot Sensing Technology

A sophisticated machine run by a computer is an intelligent robot. It possesses limbs and sensory abilities that are similar to those of humans, flexible action programs, and some level of intellect. It is capable of operating without human intervention. The control of robots is greatly aided by intelligent robot sensors. Robots' resemblance to humans in terms of perceptual processes and response capacities is a result of the sensors. Tactile sensors, visual sensors, force sensors, proximity sensors, ultrasonic sensors, and auditory sensors are installed on the robot to detect the work object, the environment, or the relationship between the robot and them. This greatly improves the robot's working conditions and allows it to more fully complete complex work.

Intelligent machine sensing technology uses sensors to realize tactile or non-tactile information fusion calculation and has the ability of comprehensive analysis. UAVs are used as carriers. The sensor is used to obtain the data of the live operation of the distribution network, and the safe distance of the live operation of the distribution network is determined through intelligent analysis. Figure 3 shows the safe-ranging process of the live operation of the UAV distribution network integrating the intelligent robot sensing technology.

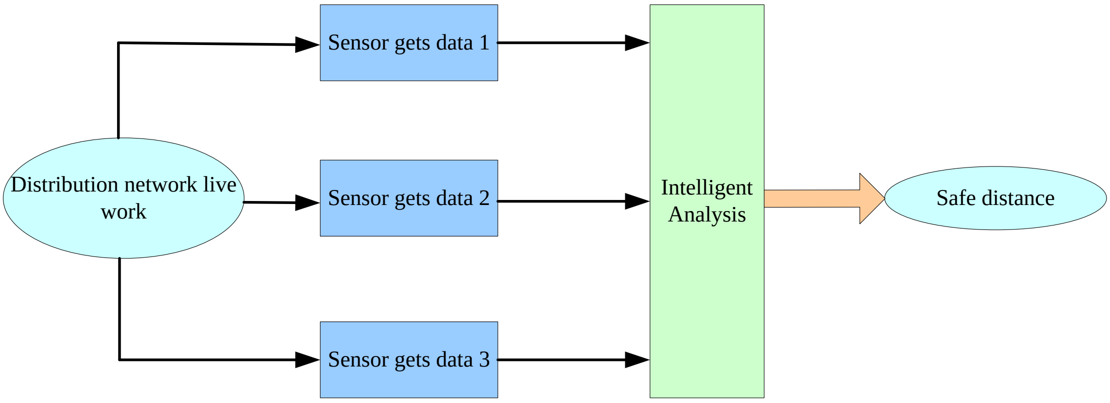


Figure 3. Process diagram of safe distance measurement integrated with intelligent robot sensing technology

The distribution network's real-time data is obtained by the UAV in Figure 3 via sensing equipment, and the safe distance is computed by intelligent analysis. In intelligent analysis, data processing is mainly carried out through artificial neural networks. Artificial neural network has excellent multi-data generalization processing and predictive analysis capabilities. It is very suitable for measuring the safety distance in the live work of the distribution network.

In the artificial neural network, the information processing unit is the artificial neuron. The data set of live operation of distribution network obtained by UAV is set to $X = (x_1, x_2, \cdots, x_n)$, and the connection weight between each intelligently processed data and artificial neurons is $V = (v_1, v_2, \cdots, v_n)$, and then the data processing process of safe ranging in the live work of the distribution network is as follows:

$$h = \sum_{i=1}^{n} x_i v_i \tag{1}$$

In Equation 1, h represents the summation of weights on the input data. The processing result of the artificial neuron is expressed as:

$$y = s(h) \tag{2}$$

In Equation 2, the $s()$ function is the activation function.

The most frequently used structure in artificial neural networks is the reverse error propagation structure. The reverse error propagation neural network has two directions of information propagation. The core mechanism is to adjust the structure of the neural network through the reverse propagation of errors, to make the output data more accurate [23]. The back-propagation neural network has a three-layer structure, and the connection weights of each adjacent two layers are represented by v_{ij} and v_{jk}, respectively.

The following is the expression for the forward propagation procedure of safe ranging during distribution network operation in real-time:

The output signal of the input layer is expressed by the formula:

$$x_j = \sum_i v_{ij} x_i \tag{3}$$

The output of the hidden layer can be expressed as:

$$s(x_j) = \frac{1}{1+e^{-x_j}} \tag{4}$$

In Formula (4), $s()$ represents the activation function, which is generally a step function.

The result of the output layer is:

$$x_k = \sum_j v_{jk} s(x_j) \tag{5}$$

In the back-propagation process of safe ranging in the live operation of the distribution network, the error of back-propagation should be calculated first, and the error is expressed as:

$$E = \frac{1}{2}\sum_k (x_k^a - x_k^b)^2 \tag{6}$$

In Formula (6) x_k^a and x_k^b shows the difference between the anticipated and actual output, respectively.

Assuming that the acceptable error size of safe ranging in the live operation of the distribution network is e, then $E > e$, it means that the error is not within the acceptable range, and the actual output is close to the expected output by adjusting the structure of the neuron. When $E \leq e$, it means that the error reaches an acceptable range, and the back-propagation neural network calculation is completed [24].

6. Experiment of Safe Distance Measurement for Live Work in Distribution Network

6.1. Data Sources for Safe Distance Measurement for Live Work

The risk of live work in the distribution network is high, and safe ranging is an effective protection for circuits and construction personnel. To better analyze the performance of safe distance measurement in the live operation of the distribution network, the experiment would carry out a questionnaire for the close contacts during the live operation of the distribution network. Among them, there are 300 construction personnel for live work in the distribution network and 200 power grid management personnel. The main statistics are the indicators they think can evaluate the safe-ranging performance of live work [25-26]. The statistical results of safe-ranging data for live work in the distribution network are shown in Table 2.

Table 2. Statistical table of safe-ranging data for live work in the distribution network

Serial number	Index	Number of people (person)	Proportion
1	Safety for live workers	120	24%
2	Accuracy of safe-ranging	90	18%
3	Stability of Power Transmission	90	18%
4	Line availability	70	14%
5	Efficiency of live work	130	26%

In Table 2, the indicators that 500 people who are in contact with live work in the distribution network think that they can evaluate the safe distance measurement are counted, of which the most agreeable number is the efficiency index of live work. The proportion is 26%. The second is the safety index of live workers, accounting for 24%.

The correlation analysis of the safety ranging of distribution network live work is carried out on the five indicators in Table 2. The correlation analysis is to study whether the indicators can be used to evaluate the performance of safe ranging [27]. Table 3 displays the findings of the safety ranging correlation study on relevant metrics.

Table 3. Results of Correlation analysis

Serial number	Index	Correlation
1	Safety for live workers	0.28
2	Accuracy of safe-ranging	0.22
3	Stability of Power Transmission	0.20
4	Line availability	0.06
5	Efficiency of live work	0.24

In Table 3, the correlation results of five indicators are analyzed. The highest correlation index is the safety of live workers, followed by the efficiency of live work. The smallest correlation index is the availability rate of the line, and the correlation is only 0.06. Since the correlation of the line availability index is too low relative to the other four indexes, in the following experimental analysis, the line availability index would not be analyzed [28].

6.2. Experimental Design of Safe-Ranging

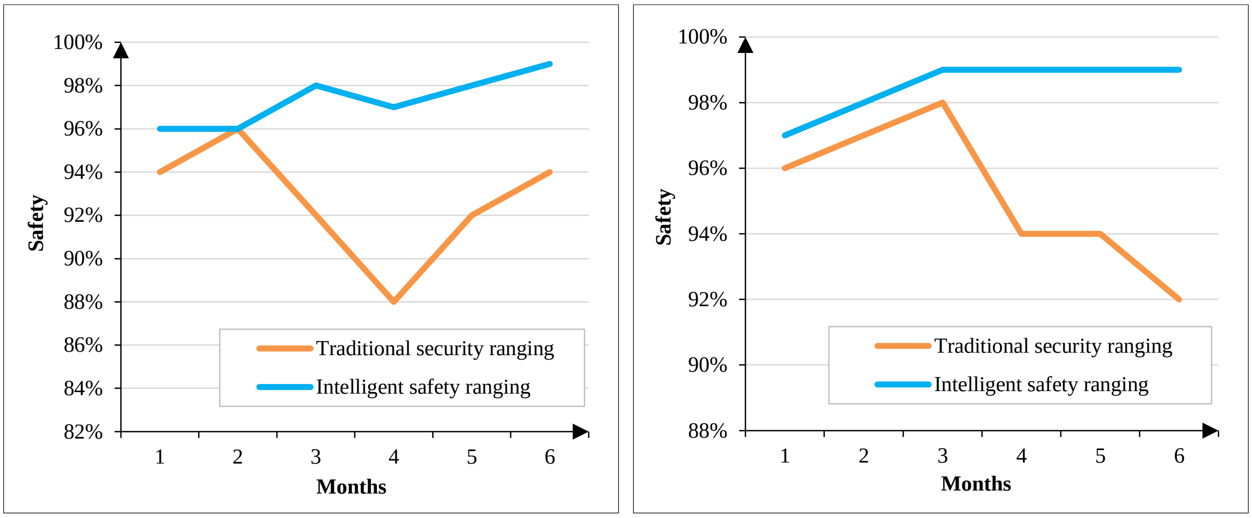
To analyze the effect of safe distance measurement of live operation based on intelligent robot sensing technology, a comparative analysis would be made with the traditional live distribution network safe distance measurement. Among them, the UAV integrated with intelligent robot sensing technology uses the back-propagation neural network as the core of data calculation, which is recorded as intelligent safe ranging. However, the traditional live distribution network safety ranging is for the construction personnel to perform safe ranging according to experience, which is recorded as traditional safe ranging.

Intelligent safe-ranging is a process of comprehensive data analysis. For example, the data obtained by drones for live work in the distribution network include voltage, air humidity, air temperature, altitude, etc., and use Formula (1) to process these data. The actual safety distance is obtained through the calculation of the back-propagation neural network, and the error analysis is carried out $E = \frac{1}{2}\sum_k (x_k^a - x_k^b)^2$ until the error reaches an acceptable range.

When comparing the two safe-ranging methods, since the voltage is the main factor affecting the safe distance, it is necessary to set up a comparison experiment with different voltages. The experiment would be set up for half a year, and the data of the safety ranging evaluation index would be counted every month [29, 30].

7. Results of Safe Distance Measurement for Live Work in Distribution Network

The safety of live workers: There is a great deal of risk involved in performing high-altitude maintenance, which is necessary for the distribution network's live operations. The distribution network's live construction workers' safety can be successfully safeguarded by safe ranging. Two methods of safe ranging are compared and analyzed. The safety comparison results of live workers under live work with different voltages in China in 2020 are shown in Figure 4.

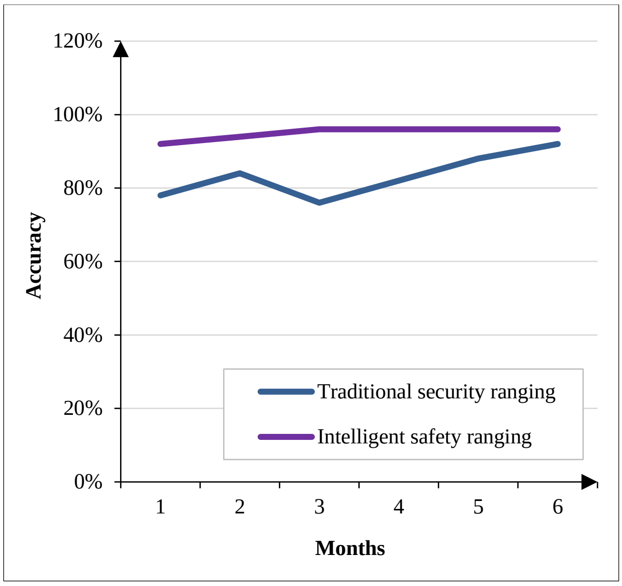


(a) High voltage (b) Low voltage

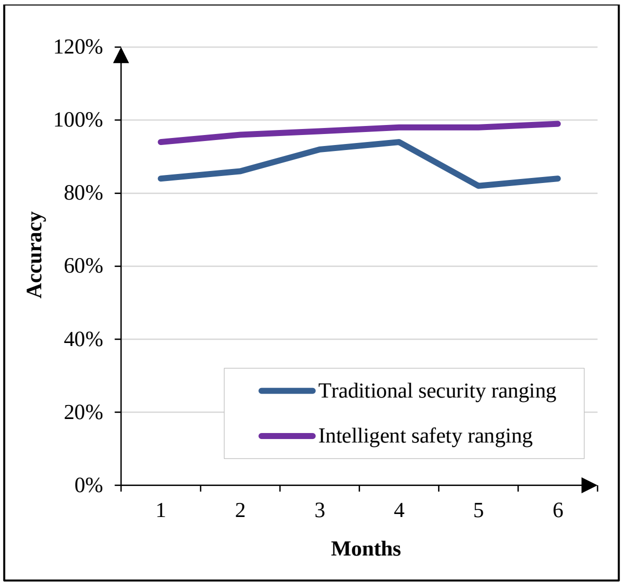
Figure 4. Safety comparison results of live workers

In Figure 4(a), it is a comparison of the safety of live workers on high-voltage lines with two safety-ranging methods. Among them, the safety of live workers under traditional safety ranging reached a minimum of 88% in the fourth month and a maximum of 96% in the second month. However, the safety of live workers under intelligent safety ranging has reached 96% and above, and with the implementation of intelligent safety ranging, the overall safety of workers is on the rise, reaching 99% in the sixth month. In Figure 4(b), it is a comparison of the safety of construction workers on low-voltage lines. The safety of the live worker under the intelligent safe-ranging mode is higher than that of the live worker under the traditional safe-ranging mode within 6 months of the experiment. Electrical worker safety is 92% and 99% for both safe-ranging methods in the sixth month. Therefore, the safe distance measurement of UAV distribution network live work integrating intelligent robot sensing technology can effectively improve the safety of live workers.

Accuracy of safe ranging: The most important thing for the safe distance measurement of live work is the accuracy of the distance measurement. Statistics were carried out on the accuracy of the safe ranging of the two safe ranging methods in 2020. Since the safety distances of different voltage intensities are quite different, it is necessary to compare and analyze high-voltage lines and low-voltage lines separately [31]. The comparison results of the safety ranging accuracy of the two safe ranging methods for live work in distribution networks are shown in Figure 5.



(a) High voltage



(b) Low voltage

Figure 5. The accuracy comparison results of safe-ranging

In Figure 5(a), it is a comparison of the accuracy of safe ranging on high-voltage lines, in which the accuracy of traditional safe ranging fluctuated within 6 months of the experiment, and reached the maximum in the 6th month. The safe-ranging accuracy was 92%. The safe-ranging accuracy at this time was 92%. However, the accuracy of safe ranging under intelligent safe ranging is constantly improving, reaching convergence in the third month, and the accuracy from the third month to the sixth month was 96%. In Figure 5(b), the accuracy of safe ranging is compared for low-voltage lines. The accuracy of traditional safe ranging fluctuated during the experimental period, and the accuracy was 84% in the sixth month. The accuracy of intelligent safety ranging is continuously improved due to the enhanced learning ability of the neural network system, reaching a maximum of 99% in the sixth month. Therefore, intelligent safe ranging has higher ranging accuracy and would become more and more accurate.

Stability of power transmission: The purpose of live work in the distribution network is to achieve stable transmission of electric energy. If the safety distance measurement is more accurate, the construction personnel would be more efficient in live work and improve the stability of power transmission. A half-year power transmission stability test was carried out on the two safe distance measurement methods for live work in distribution networks. The comparison results of power transmission stability are shown in Figure 6.

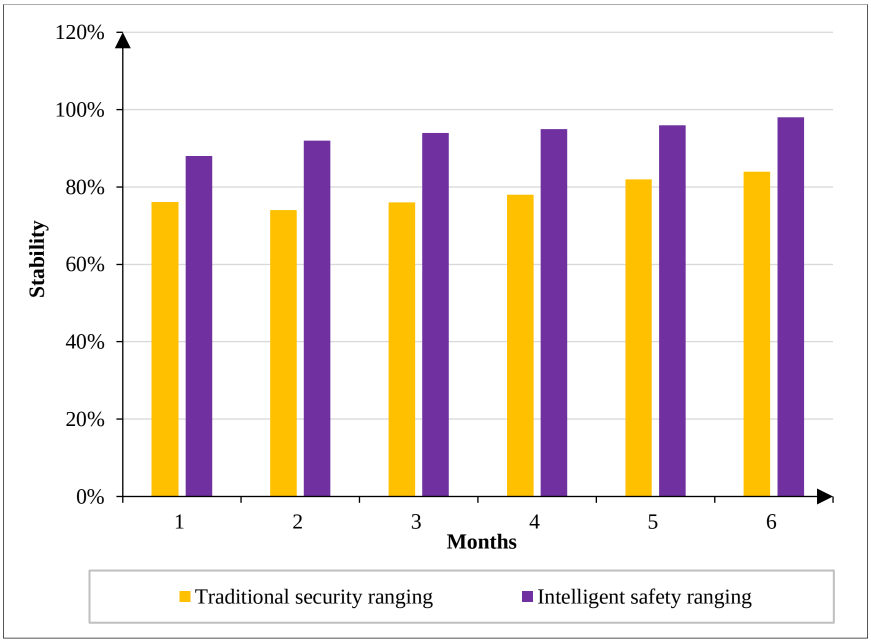
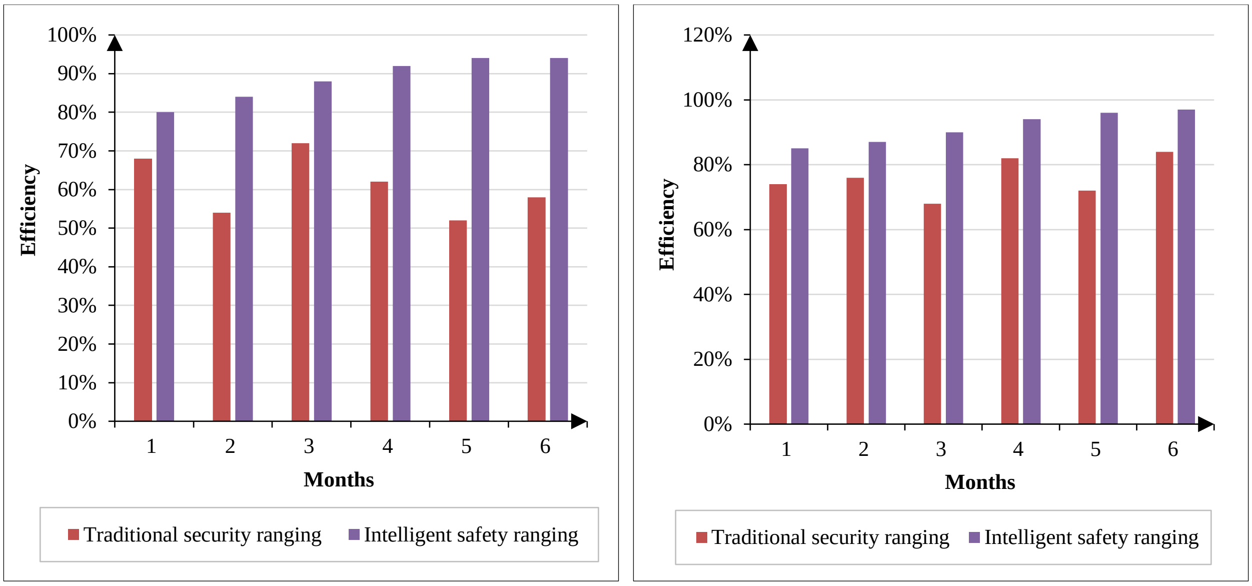


Figure 6. Comparison results of the stability of power transmission

In Figure 6, the comparison of the power transmission stability under the safe distance measurement of the live operation of the two distribution networks was described. Among them, the power transmission stability of 6 months under the traditional safe-ranging method was not much different, and the power transmission stability was 78.3% on average. The stability of power transmission under the intelligent and safe-ranging method has been continuously improved, from 88% in the first month to 98% in the sixth month. Therefore, the safe distance measurement of UAV distribution network live operation integrated with intelligent robot sensing technology can effectively improve the stability of power transmission.

Efficiency of live work in the distribution network: The live operation of the distribution network is to deliver stable electric energy to various places in time [32]. The efficiency of live operation of the distribution network was compared between the two methods of live safety distance measurement of the distribution network. Due to the different effects of live work under different circuit voltages, the high voltage and low voltage were compared respectively, and the comparison results of the efficiency of live work in the distribution network are shown in Figure 7.



(a) High voltage (b) Low voltage

Figure 7. The efficiency comparison results of live work in a distribution network

In Figure 7(a), the live work efficiency of the distribution network is compared under the condition of high voltage lines. Among them, the live working efficiency data under the traditional safe-ranging method fluctuates up and down, and the average live working efficiency is 61%. However, the live work efficiency of the distribution network under the intelligent and safe ranging is constantly improving, and the live work efficiency during the experiment is higher than that of the traditional model, reaching convergence in the fifth month. The live working efficiency of the distribution network at this time is 94%. In Figure 7(b), it is a comparison of the efficiency of the live operation of distribution network on low-voltage lines. The efficiency of live operation of the distribution network under intelligent safe ranging is higher than that of traditional safe ranging. The efficiency of live distribution network work under the two types of safe ranging is 84% and 97% in the sixth month. Therefore, the safe distance measurement of UAV distribution network live operation integrated with intelligent robot sensing technology can improve the efficiency of distribution network live operation.

Accuracy: Prediction accuracy is the degree to which the model's estimated values agree with the real values. Accurate predictions are more dependable and believable; this measure evaluates the model's accuracy.

Loss: The difference between predicted and actual results is quantified by comparing the loss to the predicted values, which illustrates the model's inaccuracy. By minimizing loss and defining the variance using a predetermined metric, it produces precise forecasts. Figure 8 shows the results of Accuracy and Loss.

Study demonstrates that Unmanned Aerial Vehicles (UAVs) equipped with intelligent sensing technology achieve superior accuracy in safe ranging for live work. Integrating UAVs with intelligent sensing technology can significantly enhance safety and efficiency in live work, mitigating risks associated with high-voltage circuits and ensuring stable energy transmission in distribution networks.

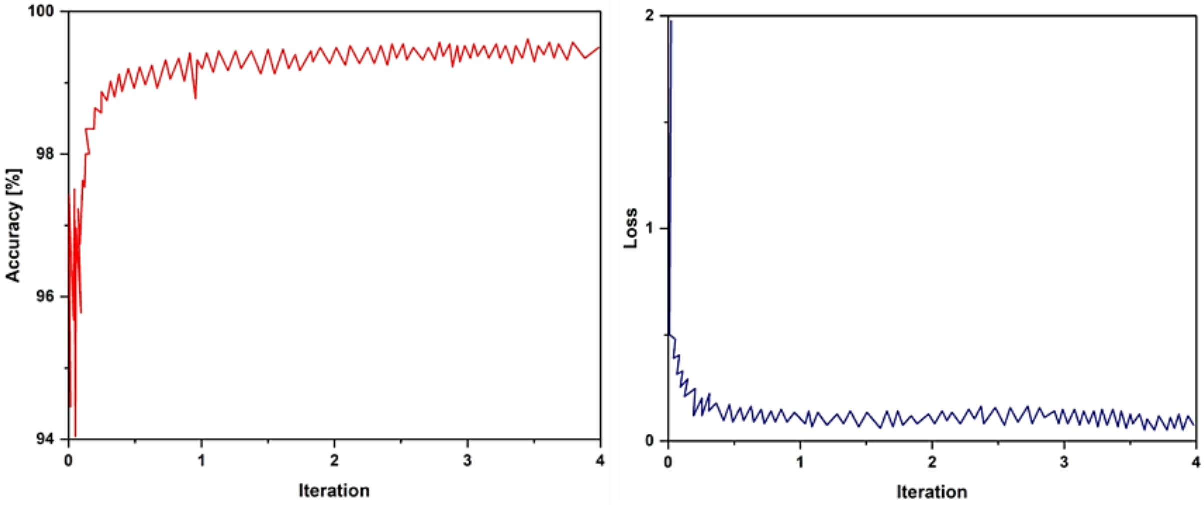


Figure 8. Results of Accuracy and Loss

8. Conclusion

Enhancing Live Work Safety focuses on improving safety measures in work environments where employees are directly exposed to electrical hazards, such as distribution networks or power plants. The integration of Unmanned Aerial Vehicles (UAVs) with intelligent robot sensing technology emerges as a transformative solution to address the safety and efficiency challenges inherent in live work on distribution networks. This study underscores the critical importance of accurate safety distance measurements in mitigating risks associated with high-load electric energy transmission, highlighting the indispensable role of UAVs in enhancing worker security and operational reliability. The comparative analysis conducted in this study reveals convincing verification of the effectiveness of UAVs equipped with intelligent sensing technology. With accuracy rates of 92% and 96% for high-voltage circuits and 84% and 99% for low-voltage circuits, respectively, UAVs demonstrate a clear advantage over traditional live work techniques. These findings underscore the potential of UAVs to revolutionize safety protocols and standard practices in distribution network maintenance. By leveraging advanced sensing capabilities and unmanned aerial platforms, UAVs offer exceptional precision and reliability in safety distance measurements. Moreover, the adoption of UAVs in live work safety distance measurements represents a paradigm shift towards data-driven decision-making and automation in electrical infrastructure maintenance. The integration of UAVs with intelligent sensing technology offers significant advancements in safety for live work on distribution networks. However, challenges exist, such as environmental dependencies and line-of-sight restrictions, which can affect reliability, particularly in adverse weather or densely populated areas. Additionally, scaling UAV deployment and ensuring cost-effectiveness remain areas for exploration. Further research is needed to refine UAV technologies, optimize deployment strategies, and explore integration with AI and autonomous systems for maximum effectiveness.

9. Declarations

9.1. Author Contributions

Conceptualization, Y.J. and X.P.; methodology, X.P., Z.Z., H.J., and J.S.; software, Y.J. and P.Z.; validation, Y.J., X.P., and Z.Z.; formal analysis, Y.J., L.W., and J.S.; investigation, X.P. and L.W.; resources, Y.J. and P.Z.; data curation, Z.Z., H.J., and P.Z.; writing—original draft preparation, Y.J., X.P., and H.J.; writing—review and editing, L.W. and J.S.; visualization, Y.J. and H.J.; supervision, Y.J. and Z.Z.; project administration, Y.J., X.P., and Z.Z.; funding acquisition, Y.J. All authors have read and agreed to the published version of the manuscript.

9.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

9.3. Funding

This research study is sponsored by Science and Technology Project of State Grid Corporation of China. The name of the project is Research and Development of an Intelligent Safety Monitoring System for live operations in a distribution network based on UAV AI recognition. The project number is TSS2020-05.

9.4. Institutional Review Board Statement

Not applicable.

9.5. Informed Consent Statement

Not applicable.

9.6. Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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