



Unmanned Aerial Vehicle for Transmission Line Inspection: Status, Standardization, and Perspectives

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As the biggest country in power consumption and generation, China owns the largest scale of transmission line worldwide. The application of unmanned aerial vehicle (UAV) in inspection has been carried out for many years in China because of its strong adaptability and safety compared to the traditional manual way. For the further development of UAV application technology in transmission line inspection, China has accumulated rich experiences and greatly improved line inspection efficiency and formed a relatively complete UAV transmission line inspection standardization system including operation safety management, an equipment configuration method, and functional quality requirements. However, there still exist some obstacles that need to be tackled due to the fact that China's UAV transmission line inspection standardization and its international promotion have not been thoroughly and comprehensively studied at present. Based on an in-depth analysis of China's current UAV transmission line inspection standardization system, this study employs SWOT-PEST analysis to insightfully investigate international promotion opportunities/challenges under the current situation, upon which several constructive suggestions are proposed from four aspects of politics, economy, society, and technology. The ultimate purpose is to design feasible schemes to boost the international promotion of China's UAV transmission line inspection standardization and further development of international UAV inspection technology.

Keywords: UAV, transmission line inspection, standardization, promotion, SWOT analysis

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Edited by:

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Specialty section:

This article was submitted to
Smart Grids,
a section of the journal
Frontiers in Energy Research

Received: 23 May 2021

Accepted: 11 June 2021

Published: 07 July 2021

Citation:

Li X, Li Z, Wang H and Li W (2021)
Unmanned Aerial Vehicle for
Transmission Line Inspection: Status,
Standardization, and Perspectives.
Front. Energy Res. 9:713634.
doi: 10.3389/fenrg.2021.713634

INTRODUCTION

As the traditional method of transmission line inspection (Liu et al., 2019a), manual inspection has some obvious disadvantages (Muniappan, 2021) when it comes to special terrain and meteorological conditions which frequently lead to low inspection efficiency (Padhy and Panda, 2021), and personnel safety is not always guaranteed (Kumar et al., 2021). Although the United States and European countries started to use helicopters to inspect transmission lines from the middle of the 20th century, the high risk and inefficiency of manual ways have not been fundamentally addressed (FU et al., 2017). With the development of UAV application technology, UAV inspection shows its irreplaceable advantages of safety and efficiency in transmission line inspection (Kumar Injeti and Kumar Thunuguntla, 2020; Miao et al., 2020), and it has little impact on transmission lines because it can undertake on-line inspection (He et al., 2020; Liang et al., 2020).

At present, research on UAV inspection tends to focus on technologies including defect monitoring, autonomous inspection, and so forth, which can be summarized as follows:

- Research on transmission line detection technology includes the use of deep learning target identification and navigation technology, which can effectively improve the monitoring ability and reduce the inspection cost (Gangolu and Sarangi, 2020; Sui and Ning, 2021)
- The endurance of line inspection UAV is based on the flight battery optimization, UAV nest and power supply, UAV radio power transmission technology, etc. (ZHAO et al., 2017)
- Autonomous line patrol of UAV includes intelligent image data processing and autonomous intelligent line inspection, as well as the ultimate goal of the complete autonomous inspection (Tavakoli and Nafar, 2020)

This study initially investigates the characteristics of line inspection UAV and concludes that different UAV types correspond to different line inspection tasks. The development status of UAV line inspection technology is analyzed combined with the current application situation of other countries. Then, this work deeply studies China's UAV line inspection standardization system, which aims to find the international promotion path of China's UAV inspection standardization through SWOT-PEST analysis. The points are summarized as follows:

- Relying on the advantages of UAV technology, China's UAV line inspection technology is widely used and has rich experience in line inspection, which can provide efficient line inspection solutions for other countries.
- China's UAV line inspection standard has a relatively perfect system, which can provide a valuable reference for other countries to use UAV line inspection.
- Strengths-weaknesses-opportunities-threats (SWOT) analysis and political-economical-social-technological (PEST) analysis are adopted to illustrate the strengths and weaknesses of international promotion, which also discuss the opportunities and challenges.
- The promotion of China's UAV line inspection standard may be limited by laws and regulations, but it can be changed according to the actual situation to adapt to the specific situation of corresponding countries. Generally, it has strong practicability for its promotion in the world.

OVERVIEW OF UAV

UAV refers to the unmanned aircraft operated by radio remote control equipment and a self-contained program control device or operated by using an onboard computer completely or intermittently (ICAO's circular UAS, 2011). UAV was introduced for military investigation and attack in 1920s, as shown in **Figure 1**. Nowadays, it has been widely used in the civil fields including photography, security, inspection, and other industries where manual work cannot be accomplished easily. With the development of UAV technology, the range of its utilization will be much wider.

Classification of UAVs

UAV can be classified into different types according to its utilization, size, flight platform, and flight range, as shown in **Figure 2** (Hassanalain and Abdelkefi, 2017). Among them, flight platform of UAV is the most significant factor to the line inspection since it considerably affects the specific application of UAV. Moreover, different characteristics of flight platforms more or less affect the mode of line patrol. Therefore, investigation of different platforms of UAV is critical to optimize the line inspection method. Next, the classification of UAV is discussed from several main aspects of the flight platform.

- *Fixed-Wing UAV*. Fixed-wing UAVs are larger than rotary-wing UAVs under the same specifications and are more complex in taking off and landing. The fixed-wing UAV has faster speed, longer endurance, and higher flight altitude than the rotary-wing UAV (Yi et al., 2017). Fixed-wing UAVs can be used in various environments, including jungle, desert, city, ocean, and mountain areas, as shown in **Figure 3A**.
- *Rotary-Wing UAV*. Based on the rotor blade or propeller system, the rotary-wing UAVs is a smaller-size and higher-payload UAV. It has the flexibility and ability to hover in the air and go to places where fixed-wing UAVs cannot go. The rotary-wing UAV is also the cheapest compared with other types of UAV. However, its disadvantages include low endurance, instability in the wind, and limitation of flight range and altitude (Tang et al., 2018a), as shown in **Figure 3B**.
- *Flapping-Wing UAV*. Flapping-wing UAVs are based on bionics, and most of them have flexible and light wings which are important for their aerodynamic proficiency and flight stability (Chen et al., 2020), as shown in **Figure 3C**. Moreover, the flapping-wing UAV has strong adaptive wind resistance, but it is not widely used in the civil UAV field.
- *Unmanned Airship*. As an aircraft based on the principle of buoyancy, it has the fundamental characteristics of long dead time, heavy load, and stable flight, as shown in **Figure 3D**. It takes advantage of the lower stratospheric wind speed and other favorable conditions, carries the mission load, and lifts off by buoyancy, so as to realize the stable residence and controllable flight in the specific area (Fei, 2019). The technological development of unmanned airships varies from country to country, so it has not been popularized.
- *Parafoil UAV*. The parafoil UAV takes off using a powered parachute instead of wings or propellers, as shown in **Figure 3E**. It has the characteristics of strong endurance, vulgarity, low altitude, and stable flight (Guo et al., 2017). Also, it can be used in agriculture and forestry, aerial photography, aerial survey, weather modification operation, rescue, and relief.

Application of UAV

Nowadays, UAV has been widely used in various areas corresponding to its different characteristics (Tang et al., 2018b). Applications of UAV are listed in **Table 1**.

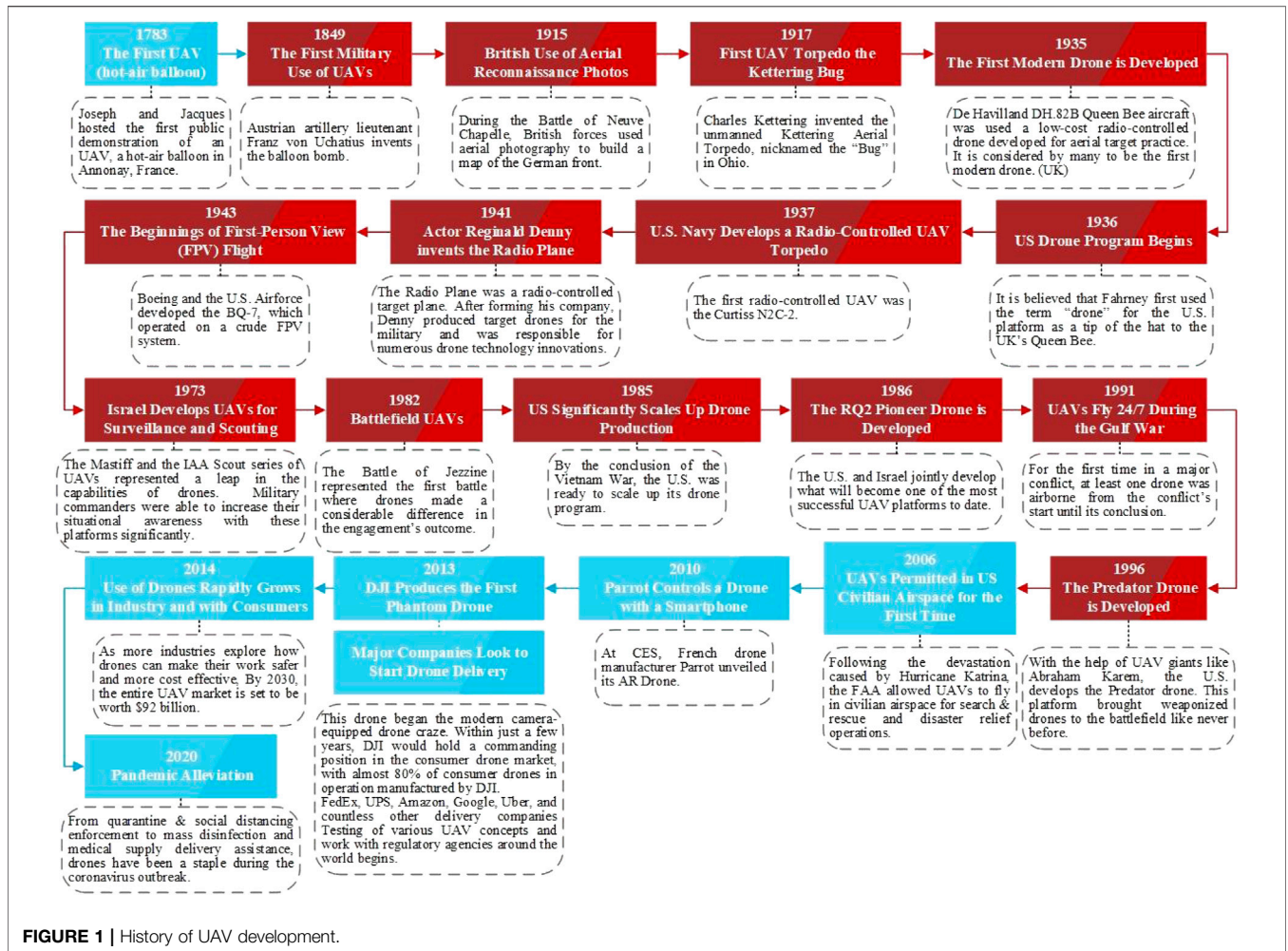


FIGURE 1 | History of UAV development.

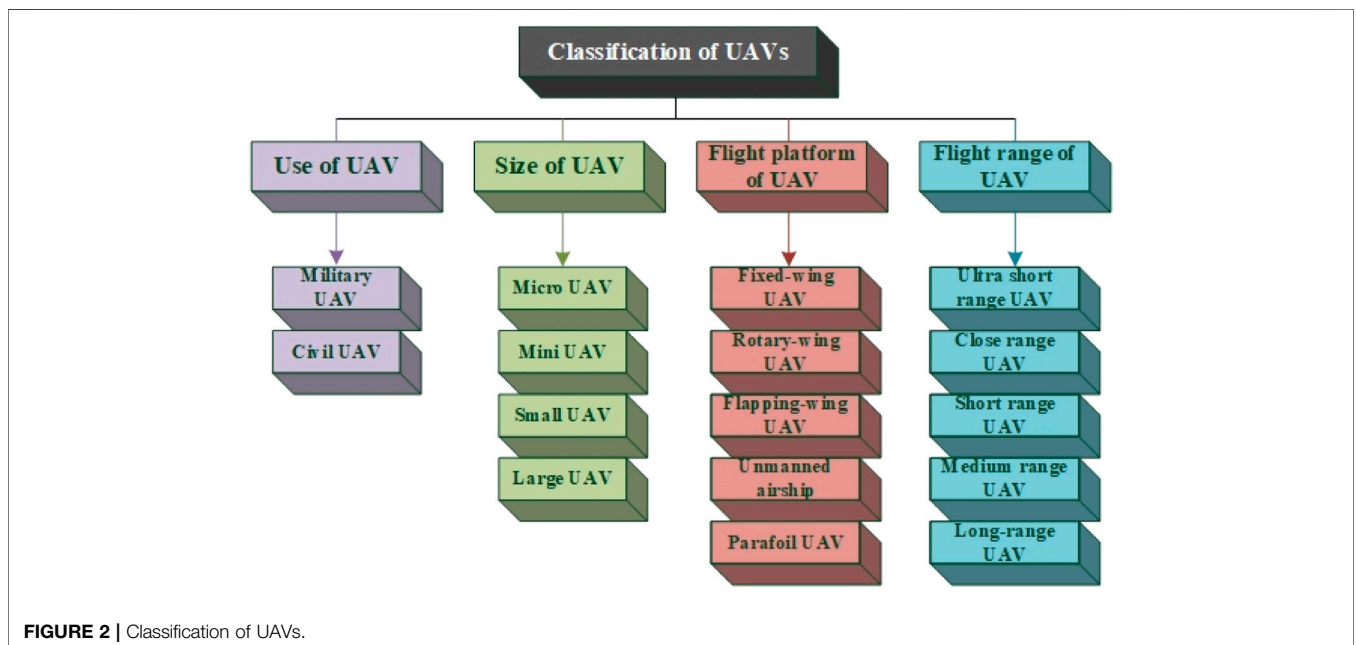


FIGURE 2 | Classification of UAVs.

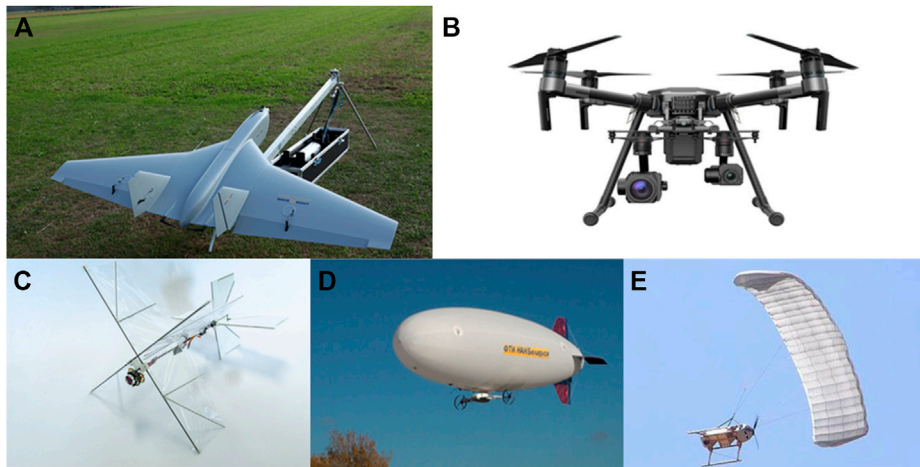


FIGURE 3 | Different types of UAVs: **(A)** fixed wing (Volt Aerial Robotics, 2016), **(B)** rotary wing (Geospatial Media and Communications, 2018), **(C)** flapping wing (Tzu-ti, 2020), **(D)** unmanned airship (Unmanned airship, 2014), and **(E)** parafoil UAV (Lanny Lin, 2021).

TABLE 1 | Application of UAV.

Application fields	Applicable UAV	Characteristics of demand
Aerial photography	Rotary-wing UAV	Easy to operate, good image transmission effect
Security	Rotary-wing UAV	Long endurance, strong adaptability to harsh environment, good image transmission effect
Inspection	Rotary-wing UAV, fixed-wing UAV	Long endurance, strong adaptability to harsh environment, good image transmission effect, stable signal, strong load capacity, easy maintenance
Others	Rotary-wing UAV, fixed-wing UAV	Long endurance, strong load capacity, strong anti-interference ability

- **Aerial Photography.** UAV can carry high-definition cameras with small volumes. Using the unique perspective of the air to record sports events, performing arts activities, and film and television shooting improves the efficiency and quality of shooting (Guo et al., 2017).
- **Security.** UAV has been more widely used in security, such as forest fire early warning, public security prevention and control, UAV security inspection, and monitoring (Volt Aerial Robotics, 2016), which can effectively supplement and strengthen the traditional security methods.
- **Inspection.** UAV inspection improves efficiency *via* the combination of visible light, thermal infrared, and lidar image fusion technology (Geospatial Media and Communications, 2018), as well as reduces the occurrence of safety accidents.
- **Others.** By improving the accuracy of mapping, UAV plays an important role in the protection of cultural relics, urban planning and water conservancy monitoring, and other applications (Unmanned airship, 2014).

APPLICATION OF UAV IN TRANSMISSION LINE INSPECTION

Economic development relies on the construction of power grid. Transmission lines are getting longer and more complex in many

countries. In 2009, China's power grid length of more than 200 kV reached 375,000 km, which surpassed the United States and ranked first in the world. By 2018, the length of the grid over 35 kV reached 1,892,000 km. Failure or loss of power may bring direct economic losses and personnel casualty. Hence, the task of transmission line detection and maintenance is of great significance. However, due to high cost, inefficiency, and high safety risk, traditional methods for manual line inspection have many drawbacks in operation, which cannot meet the needs today. UAV inspection can make up for the deficiency of manual way and become the mainstream tool of the future of line inspection (Singhal et al., 2018).

Manual Vs. Unmanned Aerial Vehicle Transmission Line Inspection

The transmission line inspection task involves mapping and inspection of transmission line components, vegetation encroachment monitoring, icing detection and measurement, and disaster monitoring. Manual and UAV line inspection have their own advantages and disadvantages, respectively.

Manual line inspection has the disadvantages of large labor, long inspection cycle, and low efficiency. Since a lot of lines are located in the suburbs or even depopulated zones, manual line inspection requires a long trip to get there, and due to the height



FIGURE 4 | Manual transmission line inspection and UAV inspection (Manual transmission line Inspection, 2018) (UAV transmission line Inspection, 2020).

TABLE 2 | Comparison between manual line inspection and UAV line inspection.

Line inspection mode	Manual transmission line inspection	UAV transmission line inspection
Advantage	<ol style="list-style-type: none"> 1. Can work in a severe weather environment 2. Maintenance at the same time 3. Low cost of manual training 	<ol style="list-style-type: none"> 1. High efficiency 2. Low cost of equipment 3. Ensure personnel safety 4. Live working
Disadvantage	<ol style="list-style-type: none"> 1. Time consuming and inefficient 2. High safety risk 	<ol style="list-style-type: none"> 1. Restricted by harsh climate 2. High cost of training

of the power tower (the general tower is 30–50 m high and the ultra-high voltage tower is 100 m high), technicians need to climb up and inspect the defects under live working, as shown in **Figure 4**. However, manual inspection can operate in extremely low temperature and high-altitude areas when most UAVs cannot operate normally. In addition, manual line inspection can repair the equipment in the process of line inspection, but UAV cannot yet (Peng et al., 2016).

Compared with manual inspection, UAV has lower equipment cost and higher line inspection efficiency. In the process of line inspection, UAVs can not only ensure the safety of personnel but also ensure the normal operation of transmission lines because they can do the living work. With the development of technology, UAVs may operate more complex inspection with even simple maintenance. Therefore, UAV inspection has high performance and application potential (Liu et al., 2019a). Comparisons between manual line inspection and UAV line inspection are listed in **Table 2**.

Current Status of Unmanned Aerial Vehicle Transmission Line Inspection

With the development of UAV and airborne sensor technology, multisensor cooperation can be realized, which improves the accuracy and automation of equipment defect judgment. Through UAV equipped with some infrared, ultraviolet, camera, and other equipment, hidden trouble in the budding state can be located and found in time, and the fault can be eliminated to protect the safe operation of the transmission line

(Hu et al., 2018). Then, the abnormal point of transmission line fault is inquired by the equipment carried, and then, the fault point is photographed in hover to obtain more obvious information, which is prepared for subsequent image processing and decision making.

According to the different working principles, the imaging loads applied in UAV inspection can be divided into three categories, namely, a visible imaging load, an infrared imaging load, and an ultraviolet imaging load, as shown in **Figure 5**. Infrared imaging load is mainly used for accurate and efficient detection and identification of abnormal heating defects of power transmission equipment in the process of power operation. The visible and infrared image fusion process is shown in **Figure 6**. Ultraviolet imaging technology is a kind of inspection technology for abnormal corona discharge and surface local pollution of transmission equipment.

Airborne lidar technology is the most representative technology for detecting the safe distance between line and ground objects. It can obtain reliable and accurate three-dimensional topography and feature information of the corridor, mainly including power towers, green trees, and tall buildings.

However, UAV line inspection technology has not been widely used in the world until now. From the early 20th century, some developed countries carried out UAV line inspection on transmission lines, including routine inspection, live maintenance, and other aspects. Nowadays, China’s UAV application in transmission line inspection is at the top of the world.

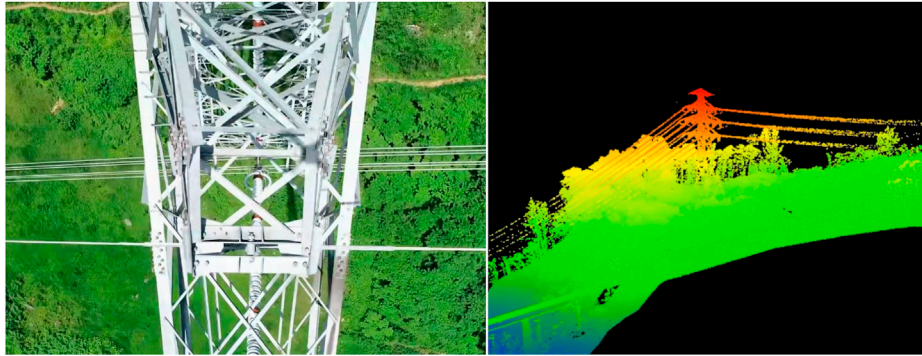


FIGURE 5 | Visible and infrared images.

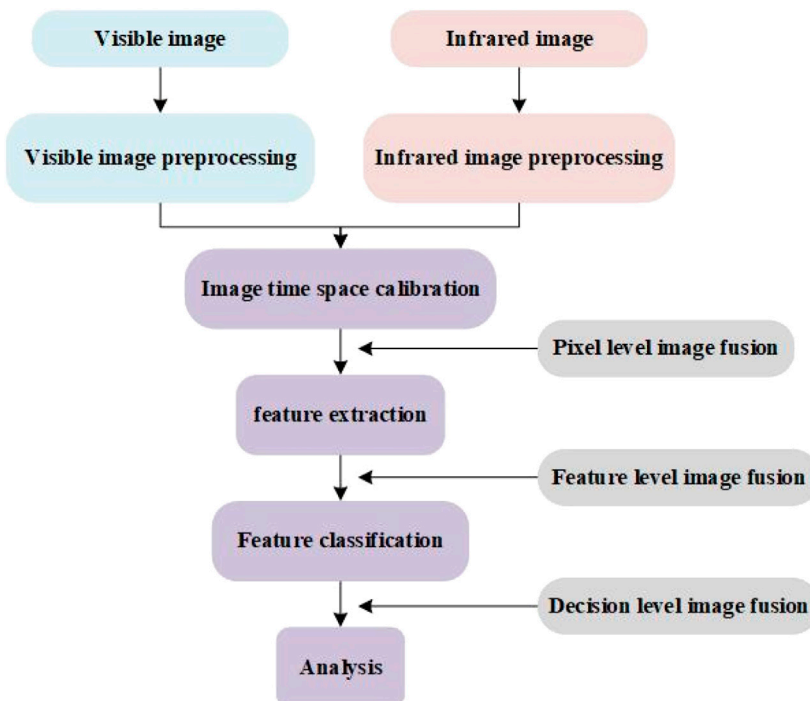


FIGURE 6 | Visible and infrared image fusion process.

Current Status of Unmanned Aerial Vehicle Transmission Line Inspection in China

From around 2010, China's electric companies have made achievements in UAV inspection and taken corresponding measures to promote the development of UAV application in line inspection. The Shandong Electric Power Research Institute and Luneng Company have jointly developed an unmanned helicopter for transmission line inspection with a high load, high-definition, and wide-angle camera; Shanghai Electric Power Company has used a small, fixed-wing UAV for transmission line inspection, which can detect high-voltage transmission lines in real-time. The State Grid also actively

promotes the UAV line inspection work, sets up a UAV training center, conducts UAV flight technology training for power inspectors, and urges the formation of a UAV inspection team (Zhai et al., 2018).

In 2013, the China Southern Power Grid Corporation promoted the intelligent inspection mode of “machine inspection and manual inspection” for transmission lines and has fully realized the collaborative inspection mode of “machine inspection as the main and manual inspection as the auxiliary.” In 2016, the large-scale unmanned helicopter line inspection system independently developed by Guangdong Power Grid Company was applied to electric power inspection. The UAV was equipped

with a visible light camera, infrared thermal imager, ultraviolet imager, 3D lidar, and other sensors and realized real-time analysis and processing of inspection data (Qian et al., 2016). After 2019, Guangdong Power Grid established the first formal UAV patrol management center in China, which has mastered technical difficulties such as night patrol, radar positioning, laser point cloud data splicing, and laser automatic modeling. UAV has been widely used in power inspection, with an annual operation volume of more than 210,000 times, accounting for 87.5% of the patrol work, ranking first in the country (China Electric Power Enterprise Federation, 2020). In 2020, the UHV company of Southern Power Grid used UAV to inspect the UHV converter station in the Kunming North Converter Station in Yunnan Province and realized the automatic flight inspection of UAV and real-time data management and analysis, which is another milestone of UAV application in China's power grid. In 2021, Longnan power grid of the State Grid began to scale and use UAV to conduct an independent inspection. The intelligence level of autonomous inspection of UAV is standardized comprehensively, and the autonomous cruise modeling and visible light modeling of key lines in the region are completed. The three-dimensional map database of transmission line patrol path is established, and the efficiency of line inspection can be improved by using new technological intelligent equipment. China's UAV inspection technology is more and more mature, diversifying the application.

Current Status of Unmanned Aerial Vehicle Transmission Line Inspection in Other Countries

Britain. In 1995, Wales University and EA power consulting company developed and tested the robot for transmission line inspection based on the unmanned helicopter of aerobatics (Chen et al., 2011). The UAV was equipped with a high-resolution CCD color visible light camera and a stability control system to enhance its antiwind ability and realize visual tracking and online detection.

Japan. In 2010, the Kansai Electric Power Company and Chiba University jointly developed a set of UAV systems for line inspection (Montambault et al., 2010). The system had a powerful image processing and recognition function, which can automatically identify common faults of transmission equipment, such as broken wire strand, abnormal heating, and welding cracks, and carry out large-scale line corridor inspection, as well as identify the growth of trees near the transmission line and tower.

Spain. In 2000, Campoy and Mejias of Madrid Polytechnic University in Spain were equipped with a visual navigation system in UAV (Mejias et al., 2007). Through machine vision navigation combined with GPS-aided positioning, the automatic navigation function of UAV line inspection was realized. The system included the helicopter airborne subsystem and ground control subsystem. The airborne subsystem gets the real-time image and its pose information. The ground control system analyzes the information returned by the airborne system and provides navigation and control information for UAV.

STANDARDIZATION OF UNMANNED AERIAL VEHICLE TRANSMISSION LINE INSPECTION

According to GB/T 20000.1:2014 Guidelines for Standardization, standardization is an activity of establishing provisions for common and repeated use regarding actual or potential problems, as well as activity of preparing, issuing, and implementing documents aimed at the achievement of the optimum order in a context and the promotion of common benefit.

The application of standardization in scientific research can avoid repetitive work in research and shorten the design cycle of products. Technical standardization is the most basic technical and competitive requirement for industrial competition in the development of global economic integration and the guarantee to ensure that the industry can be recognized in international competition.

Standardization of China's Unmanned Aerial Vehicle Transmission Line Inspection

China has formed a relatively complete set of UAV transmission line inspection standardization after many years' development of UAV transmission line inspection. Industry standards have laid a foundation for electric power enterprises to conduct UAV line inspection, and enterprise standard has also supplemented and improved industry standard. These standards, listed in **Table 3**, standardize UAV inspection operation from the aspects of operation safety management, equipment configuration method, functional quality requirements, etc., which improve the operation safety regulations, equipment and technical conditions, and personnel training.

China's standardizations apply to fixed-wing UAV and rotor UAV patrol overhead transmission lines. Through preparing UAV line inspection, the line inspection mode and method are specified and required (China's National Energy Administration, 1482). The UAV line inspection process is shown in **Figure 7**, and the basic inspection contents are listed in **Table 4**.

Patrol Mode. It is mainly divided into careful line inspection, channel line inspection, fault line inspection, and special line inspection. The rotary-wing UAV is used in careful line inspection for the first time, such as the line body equipment and ancillary facilities and the lines with defects or abnormalities that need a fine inspection. Fault line inspection and special line inspection are mainly to find and confirm the fault point and check the equipment damage and other abnormal conditions.

Preparation before Line Inspection. The preparation before line inspection includes personnel preparation and operation preparation. The personnel should be qualified to operate UAV and have corresponding health conditions and reasonably allocated according to the line inspection task and the type of aircraft used. Operation preparation is composed of airspace declaration, field investigation, and equipment inspection. Airspace declaration of UAV inspection should be

TABLE 3 | Standardization of China's UAV transmission line inspection.

Approved time	Standard number	Standard name	Standard issuing department
2015	DL/T 1482-2015	Technical guidelines for UAV inspection of overhead transmission lines	National energy administration State grid
	Q/GDW 11383-2015	Configuration guide for UAV inspection system of overhead transmission line	
	Q/GDW 11399-2015	Safety regulations for patrol inspection of electric UAV	
2016	DL/T 1578-2016	Unmanned helicopter inspection system for overhead transmission lines	National energy administration
2018	T/CEC 193-2018	Specification for training and assessment of UAV patrol operators in power industry	China Electricity Council

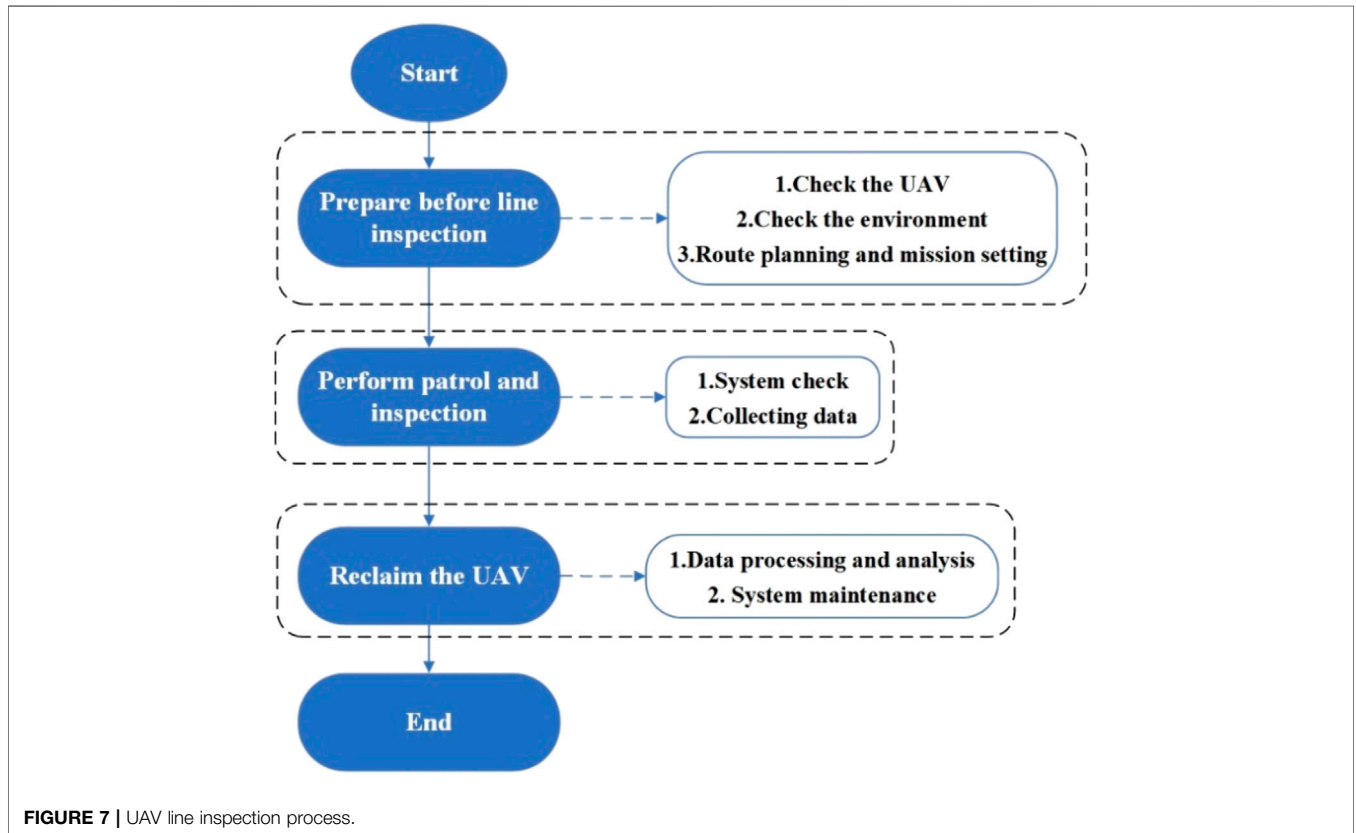


FIGURE 7 | UAV line inspection process.

TABLE 4 | Basic inspection contents.

Equipment	Visible light inspection	Infrared inspection
Conducting wire	Broken wire, obstacle, broken strand	Hot spot
Drainage line	Broken wire, obstacle, broken strand	Hot spot
Clamp	Loose	Contact hot spot
Coiled tubing	—	Heating
Tower	Damage, deformation, bolt looseness	—
Insulator	Scattered, self-exploding, obstacle	Thermal breakdown
Damper	Damage, displacement, defect	—
Accessory equipment	Defect	—
Line corridor	Geological disasters, vegetation growth, external destruction	—

carried out according to the inspection scope and relevant administrative management measures. Flight inspection requires operators to conduct field investigation in advance to verify the trajectory of the UAV inspection route and surrounding environment and find a suitable place as the

take-off and landing point. It is necessary to check the line coordinates and altitude of each tower of the inspection line and whether lines are crossing. The equipment inspection mainly contains the visible light load debugging inspection and infrared temperature measurement load debugging inspection.

Line Inspection Method. The major methods of line inspection are tower line inspection and intermediate line inspection. Rotary-wing UAV should approach the tower at low speed and hover to collect data when necessary. During patrol inspection, the distance between UAV and line equipment shall not be less than 30 m, the horizontal distance shall not be less than 25 m, and the distance between UAV and surrounding obstacles shall not be less than 50 m. The direction of the line inspection should be parallel to the direction of the ground wire in the corresponding shift. It is not suitable for medium and large UAVs to fly, hover, and cross directly above the line.

Standardization of Other Countries

To meet the standardization needs of international UAV industry development, the International Organization for Standardization (ISO) established the ISO/TC20/SC16 UAV system standardization subtechnical committee in 2014. The American Society for Testing and Materials (ASTM) has issued 12 civil UAV standards, including eight airworthiness standards, three operational standards, and one training and certification standard. There are three standards for agricultural UAV operators and maintenance in Japan, which specify the safety requirements of UAV design, overhaul, operator qualification, operation, and maintenance (Zeng et al., 2016).

The U.S.A. In 2019, the United States proposed to establish a standardized system of UAV transmission line inspection. Specifically, with energy-related UAV inspections, the American Society of Mechanical Engineers (ASME) is drafting a document of what information need inspectors and UAV owner operators need to know for such missions. The energy industry often adopts a “wait and see” approach when it comes to drones in America. To make inspections of pipelines and transmission lines over long distances practical, flights that are beyond the visual line of sight (BVLOS) are needed. However, there are legal restrictions on the flight range of civil UAVs, so the UAV inspection needs special approval and its standardization process is also more difficult.

Japan. In April 2019, Japan established a research group on UAV line inspection technology and proposed to establish a standardized system of UAV line inspection (Application report of Japan’s transmission, 2018). However, the technology of UAV line inspection still stays in the use of visual line inspection but not the radar, infrared, and other technologies. Due to the Japanese UAV laws and regulations, the problem of UAV line inspection in urban areas still needs to be solved. Japan has mature development in the usage of UAV in agriculture which can share experiences in line inspection standards setting.

European Union. Most EU standards refer to ISO and International Electrotechnical Commission (IEC) standards. Although the application of UAV in transmission line inspection is very extensive, the automatic line inspection of UAV is not mature and a standard system has not been planned yet. Legal regulations restrict the greater use of BVLOS UAVs. BVLOS UAVS need special granted permits for utilities to test.

SWOT-PEST ANALYSIS OF INTERNATIONAL PROMOTION OF CHINA’S UNMANNED AERIAL VEHICLE TRANSMISSION LINE INSPECTION STANDARDIZATION

SWOT analysis is a systematic and logical approach to investigate the internal and external factors of the studied subject, upon which the most suitable promotion mode under the current situation can be determined *via* the comprehensive analysis of related factors of the investigation subject. Meanwhile, PEST analysis refers to the specific and detailed analysis of the macroenvironment. This study combines SWOT and PEST to study the feasibility of international promotion of China’s UAV transmission line inspection standardization.

Strengths

Political

In 2018, the standardization administration of China announced the “Belt and Road” (B&R) action plan (2018–2020 years) which further defined “promoting the internationalization of China’s standards and promoting international cooperation in production and equipment manufacturing.”. Moreover, through the standards information platform established by the Belt and Road (B&R) initiative, some of China’s standards have been widely promoted around the world. Since the line inspection technology of B&R countries is not as advanced as that of China and the standard has not been formed yet, China can use its accumulated experience in this field to provide them with more services. Meanwhile, the standardization is a consequential technical basis and rule for economic and trade exchanges and industrial cooperation in promoting the B&R construction process (Shao et al., 2020).

Economical

Located in the east of Asia, China covers 9,600,000 square kilometers, with a population of 1.437 billion and GDP of 15.67 trillion US dollars in 2020 (Hu, 2021). At present, China has become the world’s second-largest economy, the largest industrial, commodity trading, and foreign exchange reserve country. Unlike other economies, China has maintained economic growth despite COVID-19, and its GDP is projected to grow by 8.4% in 2021, according to the International Monetary Fund. The booming economy provides opportunities for the technology development and promotion of the standardization of UAV transmission line inspection.

Social

With the commercialization of civil UAV, people have a deeper understanding of UAV and a higher degree of acceptance. At the same time, UAV application reduces the risk and cost of line inspection, providing more options for power companies and creating new jobs. 5G technology and the application of artificial intelligence will further improve the efficiency of line inspection. China’s line inspection UAV has more functions and more

reliable technology, and the key is low price and high-cost performance. These advantages add a greater attraction to the promotion of China's UAV line inspection standard.

Technological

China owns a variety of key technologies of UAV inspection and has rich experience in operation. In 2013, China Southern Power Grid Company (CSG) began to promote the mechanical patrol operation of transmission lines and established the mechanical patrol operation center in 2015. Focused on the development of power UAV application capability, this operation center issued the standard system and carried out the key technology research work.

At present, lidar technology and RTK technology are the main means of UAV autonomous inspection (DUAN, 2016). Using CW lidar, CSG realized the measurement of safe distance between the conductor and ground. With the help of Internet of Things technology, the State Grid Corporation of China and CSG upload UAV inspection data to the data cloud in real time and use the deep neural network algorithm, big data, and image recognition technology to automatically analyze inspection data and accurately find defects and generate inspection report. In the UAV line inspection, the defect intelligent recognition technology is adopted. Through the UAV inspection image intelligent recognition algorithm, the manual interpretation of inspection images is gradually reduced or even replaced, so as to realize the practicability of artificial intelligent recognition technology (Cui, 2016). These key technologies in inspection lay the foundation for the popularization of China's UAV inspection standards.

Weaknesses

Political

China lacks an effective platform for the application and promotion of standards abroad, and the communication channels among the government, industry, and enterprises are limited. For the internationalization achievements of key technical fields and helpful standards, there is insufficient cooperation and exchange between governments. Meanwhile, European and American standards are still dominant in many fields, so China's standards encounter great difficulties in the promotion and application.

Economical

COVID-19 has led to a global recession and severely hampered international economic cooperation, and most of the cooperation projects between China and other countries are blocked. Under the global environment of economic downturn, China's exported products may face high import taxes, which is not conducive to the promotion of China's UAV inspection standards.

Social

UAV application in transmission lines includes equipment maintenance and technical personnel training. UAV may encounter various technical obstacles and damages in the process of inspection. Simple faults may be solved on site, but for some complex problems of UAVs, they can only be returned to the manufacturer for maintenance, which increases the

maintenance cost of line inspection UAVs. Furthermore, since the training of line inspection UAV operators is not common in the world, for countries with less-developed technology, the cost of training UAV operators will increase. This will hinder the promotion of China's UAV line inspection standards.

Technological

It is difficult to break through the technical level of UAV line inspection. Although China's enterprises have abundant funds and numerous technical personnel teams, the development of UAV is still facing a strong technical bottleneck, endurance and weather resistance, which greatly limits the application of civil UAV (Liu et al., 2019b). Besides, there are professional UAV line inspection operation training institutions in China, such as the UTC training center in DJI, which can provide training and issue flight certificates for UAV line inspection operators. However, the number of operators who meet the UAV flight qualification is still very limited, and a large number of UAV operators need to be trained to realize UAV line inspection widely.

Opportunities

Political

The B&R initiative has been promoted by the Chinese government, and foreign cooperation between the relevant enterprises was benefited from it. At the same time, China continues to improve the national innovation system, speed up the construction of a powerful country in science and technology, and strongly support the development of UAV and other new technologies.

Economical

In the 14th five-year plan (2021–2025), China clearly points out that it is necessary to improve the overseas production service network and circulation system, accelerate the international development of producer services such as finance, consulting, accounting, and law, and promote the going out of China's products, services, technology, brands, and standards. The Chinese government will improve the integrated regulatory system for domestic and foreign trade and promote the convergence of laws and regulations, regulatory system, business qualifications, quality standards, inspection and quarantine, certification, and accreditation. These measures provide a good business environment for China's economy in the future. Meanwhile, the international economy will usher in a great recovery with the increasing coverage of COVID-19 vaccine, which has laid an economic foundation for the international promotion of China's UAV line inspection standardization.

Social

Language is an important factor for the international promotion of Chinese UAV line inspection standards. At present, some translators do not understand UAV line inspection technology while the operators and engineers are not proficient in foreign languages. The shortage of professional translators may lead to the problems of incorrect or inconsistent expression of technological

terms. Translation should be faithful to the original, not only to meet the requirements of grammar and correct expression of content but also to reflect the professionalism and standardization, so as to avoid multiple foreign expressions in the same Chinese professional vocabulary, ambiguity, and misunderstanding (Chen and Zhang, 2020).

Technological

China's artificial intelligence development has achieved a desirable technical goal, and 5G network construction has basically reached the annual goal. With the steady development of these two technologies, artificial intelligence will further enhance the intelligent interaction, information processing, analysis, and decision-making capabilities of UAVs, while 5G will improve the communication and data transmission capabilities of UAVs. The two will jointly release more potential power in the international promotion of China's UAV line inspection standard.

Threats

Political

For developing countries or less-developed countries and regions, their national standards are missing or not perfect. For example, the technical indicators of most central Asian countries still follow the standards of the former Soviet Union from the 1960s to the 1970s (Ma and Ma, 2018). The lack of a top-level strategy, planning of related promotion work, professional promotion personnel, and institutions, especially the lack of systematic, mature, and effective application, creates challenges for the local application of China's UAV line inspection standard.

Economical

Since 2018, trade frictions between China and the United States have escalated to many fields such as trade, science and technology, finance, and international rules, which has led to a dramatic impact on the global economy. Although vaccination has brought hope to stimulate economic activity and expand investment, the continuous economic stimulus policies around the world, especially the unprecedented scale of the US stimulus plan, have also triggered concerns about economic overheating and rising inflation expectations.

Social

The projects invested in many countries are generally required to follow European or American standards, and the acceptance of China's standards is not very often. Usually, the standards of these projects have been clearly implemented in bidding documents. At the same time, it may be restricted by law in some countries, and the promotion of China's UAV line inspection standard may need to make corresponding changes.

Technological

The system of standards is distinctive in different countries. Relevant technical standards in the United States are prepared and adopted voluntarily by industry organizations, institutions, and enterprises according to the technical regulations issued by

the government. EU standards which are formulated by government agencies are part of the regulations, and most of them are mandatory. China's technical regulations and standards are governed by the state and are divided into four levels: national standards, industry standards, local standards, and enterprise standards. At present, China implements a standard system that combines mandatory standards with recommended standards (Chen, 2021).

Information security and personal privacy are also problems of UAV line inspection applications. It is inevitable for UAV from taking photos of buildings and roads when it conducts the line inspection, which may involve personal privacy, especially in urban areas. Moreover, how to ensure the security of information and data collected during the analysis is also a crucial issue that should be paid attention to.

CONCLUSIONS AND EXPECTATIONS

Nowadays, UAV has gradually become the main tool of transmission line inspection. Meanwhile, the standardization of such industry further accelerates the promotion of line inspection technology. Based on the analysis of the promotion of UAV line inspection *via* the SWOT analysis method, the following conclusions can be summarized:

- (a) China's civil UAV technology is at the leading level in the world, which has abundant experience and advanced technologies. Thus, China's UAV line inspection standard can be used as a reference standard for other countries, which can help them to promote such industry in a more reliable and fast way.
- (b) China's UAV line inspection standards may be limited by laws and regulations in other countries, and the acceptance of Chinese standards in other countries is also relatively low. Therefore, China's standards can be correspondingly changed according to the actual situation of other countries, and China's UAV line inspection technology can also act as an important driving force for promotion.
- (c) China is the main member of the Belt and Road Initiative and the global destiny community, which needs to take the responsibility to promote China's technology around the world. In this context, the promotion of China's UAV line inspection standard will be strongly supported, which will contribute to the development and popularization of international UAV line inspection technology.

The existing standards of UAV inspection enable electric power companies to use UAVs for routine patrol tasks, but for the future development and application of patrol technology, there still exists a lot of room for UAVs to exploit for more advancement. With the development of UAV technology, the merits of UAV such as high economy, strong flexibility, and not restricted by terrain make it a hot research topic in transmission line inspection. There are some prospects for future development of UAV inspection.

Autonomous inspection: Manually manipulated UAV inspection is extremely complicated and difficult for the flyer, and there is a great demand to develop an intelligent UAV for autonomous inspection. The inspection results of different manual operation modes may vary greatly, and the inspection of overhead transmission lines is mostly cyclic and repetitive work. Relying on the operators completely will cause the problems of high labor intensity and low inspection efficiency, which will make it difficult to adapt to the new needs of power operation and maintenance. Therefore, autonomous inspection has become one of the research directions.

Battery life improvement: On the other hand, the lack of UAV range is a bottleneck problem that limits the promotion of the mounted UAV power patrol mode, and the current stage of application in the field of power inspection of small- and medium-sized multirotor UAVs in the patrol grid technology inspection load after the endurance of the patrol to maintain 10–30 min inspectors need to frequently replace the battery, which seriously affects the efficiency of inspection. In the future, it is also possible to improve the endurance of UAVs by using nest power supply.

Auxiliary maintenance: UAV can carry out not only defect monitoring but also simple maintenance operations. In the field of UAV auxiliary maintenance, we need to actively explore new technologies, including developing live water flushing, emergency lighting, and equipment anomaly detection based on voiceprint recognition, in order to further expand the application of UAV in inspection.

The last is the maintenance of UAV. In the aspect of UAV maintenance, the maintenance manual is formulated for the whole cycle process of UAV inspection, and the routine

maintenance and research work on key components of UAV is carried out. Therefore, in addition to the UAV transmission line inspection standards, it is also necessary to formulate corresponding standards for UAV maintenance.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

XL: conceptualization and writing—reviewing and editing. ZL: writing—original draft preparation and investigation. HW: writing—reviewing and editing. WL: conceptualization, resources, and supervision.

ACKNOWLEDGMENTS

We appreciatively acknowledge the support of the program entrusted by the legislative Affairs Commission of the Standing Committee of the Yunnan Provincial People's Congress (648820140054) and the Talents Training Program of Kunming University of Science and Technology (KKZ3201524007).

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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