Research and Application of Full-Link Management Intellectual Inspection Robot with Remote Pre-Control and Information Digitization

Yutao Qiu¹*, Kai Qian², Liuming Liang², Zhangli Weng², Zhen Huang², Yuchen Yan²,*
¹State Grid Zhejiang Electric Power Company, Hangzhou, China
²State Grid Ningbo Power Supply Company, Ningbo, China
*Corresponding author: 494634621@qq.com

Abstract. With the development of intelligent power grid maintenance, inspection robot has been widely used for its integrated perception and remote pre-control. Aiming at the problems of the weak information interaction capacity and the low correlation with digital requirements of inspection operation, a kind of Full-Link Management Intellectual Inspection Robot is proposed. The article introduces the system structure, function modules, engineering application and debugging process. It is with low response delay and strong anti-interference ability. The correct recognition rate of violations reached 88.2 %, meanwhile provided with the function of evaluation and early warning of workers’ unsafe behavior. The Full-Link Management Intellectual Inspection Robot has a broad application foreground in power grid maintenance.

Keywords: Management Robot; Substation; Safety tools; Information Integration; Edge computing; System design.

1. Introduction
With the development of management and equipment in power enterprises, it is more and more important to carry out digital supervision and active safety warning for equipment. In recent years, inspection robots are widely used in the evaluation and maintenance of substation equipment because of its advantages of high efficiency and low cost. Compared with the traditional manual inspection operation, it effectively reduces the accident risk of power grid, inhabitant and equipment.

Traditional applied robots in power industry have made in-depth research on robot moving mode, autonomous positioning and navigation technology, and equipment state detection technology. In foreign countries, Japan has developed an orbital mobile inspection robot equipped with infrared thermal imager and image acquisition device, which can replace manual handheld infrared thermal imager detection equipment and realize remote monitoring and observation [1]. The inspection robot developed in Canada uses flexible, simple and operable remote control mode to realize the autonomous performance of robot, and can handle the detection and recording of substation equipment [2]. Domestically, the multi-generation inspection robot developed by the State Grid Corporation of
China has proposed and developed the positioning and navigation technology based on RFID and magnetic guidance, and the automatic identification system of switches, instruments and other equipment based on visible light image analysis. It has autonomous navigation capability, and has designed algorithms for key technical points such as navigation obstacle avoidance, trajectory optimization, fault judgment, etc., which has made breakthroughs in inspection efficiency and safety performance, and achieved autonomous non-contact detection in the whole outdoor inspected area [3]. In addition, many robot R&D units represented by Tianchuang, Yijiahe, Zhongkong Guoz, Xiangchi Xinchuang, Xi'an Wali and other companies have carried out related research in multidimensional motion control, artificial intelligence algorithms, comprehensive intelligent identification and big data processing. The inspection robots produced have been put into operation in several substations in China and carried out independent inspection operations, and achieved certain results.

At present, aiming at the intelligent management of electric power overhaul and safety instruments, many units have developed handheld terminals and systems based on RFID tag technology, which have the functions of overdue return reminder and system record query [4-5]. However, from the view of actual problems in field maintenance work, the management and control system mainly relies on personnel performance, and its active management and control ability is weak; The system only records the use information of instruments, which has strong data isolation and weak information interaction ability with the operation management system, unable to take the initiative to combine the maintenance process of field work, and lacks control and feedback on the substation maintenance work.

Faced with the massive data of local on-site maintenance operations and equipment status, there are the following problems: the short of combination of inspection and maintenance business, and there is a lack of active supervision of personnel safety behavior and process; Instruments have low intelligence and weak integration ability of state communication; The system software is imperfect, and the coupling degree with daily work application is low.

To solve the above problems, this paper developed a Full-Link Management Intellectual Inspection Robot based on the whole link, and designed and implemented some key technologies such as intelligent safety equipments, field communication fusion, maintenance safety early warning, and human-computer interface interaction. The robot effectively improves the safety of on-site maintenance operation, improves the safety and stability of power grid and maintenance management level, and has broad development potential and application prospect.

2. Function Design of Full-Link Management Intellectual Inspection Robot

2.1. Task goal

Based on the cross support of electro-mechanical discipline, communication technology, sensing and control theory, the intelligent management and control robot developed in this subject focuses on the diagnosis of equipment running status and the safety management and control of field operations, and forms an auxiliary monitoring and early warning system with complete workflow, suitable for actual maintenance and platform analysis.

(1) Wheeled drive, stable mechanical structure and working performance. Realized autonomous obstacle avoidance and positioning, the motion control has strong robustness and good operability.

(2) Complete the inspection task of high-precision sampling, and monitor the status of primary equipment in the station with sensing devices such as image infrared. Strong data processing ability and high real-time performance. IOT networking architecture with integrated on-site intelligent tools.

(3) Conduct data evaluation on personnel's behavior of using safety equipments, carry out monitoring, alarming and recording work, and process the control for maintenance operations, which can guide and judge field operation steps.

(4) Friendly man-machine interaction. It can realize the viewing and operation of multi-terminal equipment.
2.2. System framework
The robot hardware measurement and control platform includes motion control module, image infrared detection unit, communication transmission module, power management module, sensing and receiving module of intelligent safety equipment, etc. MCU master controller is configured to identify the status of detection equipment and perform detection steps on the robot terminal side.

Robot software platform embeds industrial computer through Java, and performs multi-protocol communication, data stream transmission, instruction receiving and issuing, etc. Using 5G wireless transmission to realize long-distance high-definition video transmission, it can be viewed and played back in real time at the monitoring terminal level, and can access the on-site monitoring information.

![System framework](image)

**Fig1. System framework**

2.3. Design of intelligent safety equipments
Near field communication is suitable for substation maintenance work. When the robot is in the visual range of maintenance personnel and intelligent equipments, the short-range control of the robot is completed by using a low-power wireless transceiver module to reduce the data transmission delay and improve the flexibility of the robot.

Attitude sensors, communication hardware and communication protocols are selected and configured for commonly used on-site maintenance equipments such as loop resistance tester, insulated ladder, protective earth and torque wrench, so as to distribute and upload the status information of instruments and equipment to the control robot and identify whether the operation and test results are standard. Bluetooth module is installed on safety equipments such as safety helmet, fence and skip, and audible and visual warning is given to test and maintenance personnel through ranging results, so as to improve the safety of field operation.

3. Function realization of Full-Link Management Intellectual Inspection Robot

3.1. Structure of robot
The whole mechanism of the robot is made of corrosion-resistant alloy material, and the installation process of the joint of the components is optimized, so that the body structure has anti-seismic, wind-proof and rain-proof properties, which meets the requirements of industrial application. The robot body is a four-wheel drive robot, which integrates anti-collision mechanical structure, motion system, driving system, positioning system and sensing system. The robot body is made of Q235 and sprayed with anti-corrosion paint, with the protection grade of IP56, the weight of the whole car is less than 200kg, and the working temperature ranges from -10°C to 50°C.

According to the environmental characteristics of strong electromagnetic field in substation and harsh outdoor weather conditions, the hardware and software anti-interference design of the working power supply module and communication module of the control robot is carried out by using integrated modularization, shielding cover, peripheral isolation circuit, filtering algorithm and other
measures. At the same time, wide-temperature industrial-grade hardware is purchased to ensure reliable transmission of control data and normal operation of components and devices.

(1) Anti-collision mechanical structure. The car body is equipped with emergency stop switches, collision switches are arranged in front of and behind the robot, and emergency stop switches for starting are provided.

(2) Motion system. It consists of large torque BLDC, motor drive, speed reducer and manual wireless remote controller. Fuzzy PID control algorithm is used to control the car body and the assembly platform, and the response time is good. The maximum running speed of the whole vehicle can reach 1.5m/s, and the angle range of climbing $\geq 15^\circ$.

(3) Drive system. It is powered by a lithium battery pack with a working voltage of 24V, equipped with a power management optimization system, and can last up to 4 hours in a single mission.

(4) Positioning system. Using cellular mobile network positioning technology and inertial navigation technology, the positioning accuracy meets the technical requirements.

(5) Sensing system. Equipped with industrial grade network camera and infrared thermal camera, it communicates with industrial computer and server through data conversion interface, WiFi, 5G module, etc., and uploads and processes data.

3.2. Data acquisition

The robot assembly industrial computer interacts information with each sensor assembly. Taking the video data stream as an example, in Java environment, the industrial computer caches the data through rtsp streaming media protocol or uploads it to the server via network shutdown to realize offline or background online monitoring.

The robot is equipped with 5G industrial gateway and 802.11ac Wave2, which makes its coverage capacity more than 200m and can effectively meet the network coverage of working scenes. The maximum bandwidth can reach 20Gbps, and the response time is as low as 2ms, which greatly

![System Communication Topology Framework](image-url)
improves the data transmission rate, and can transmit video data, sampling data of safety equipments and infrared detection data, and ensure that data is not easy to be lost or missed[6].

When robots communicate and collect with intelligent tools, the communication protocols used by tools are different based on different usage scenarios. According to the actual usage, the following implementation methods are adopted:

LoRa. Used for communication between data detection intelligent tools and data concentrators, and can receive and parse commands forwarded by data concentrators. At the same time, it can realize the equipment handshake, data acquisition, position request and other operations according to the specific command information, which is used for the loop resistance tester and dielectric loss tester.

Bluetooth. It is used to scan Bluetooth information of personnel within 2m around the tool, which can judge the authorization qualification and position of personnel, and is used for security fence and safety helmet.

UHF-RFID. Used for equipment management of communication tools, realizing equipment positioning, usage statistics, etc.

(4) 4G/5G. It is used for information display at mobile and PC display terminals, real-time transmission and viewing of video image information, and video data transmission.

WiFi/5G. Used for receiving server control commands and uploading site collection data, used for protecting earth, insulated ladders, etc.

The communication topology diagram is shown in Figure 2.

3.3. Development method of intelligent safety equipment

As an optional sub-module of the robot, intelligent equipment is an important carrier to realize safety control of field work. In this system, 9 intelligent equipments including intelligent electronic fence, intelligent insulated ladder and intelligent helmet were developed, which were debugged by classification to collect data, and realized the functions of data record analysis, processing early warning, model training and so on.

The intelligent equipment has a digital data interface, through which the data collector can obtain measurement data. In order to realize the integration of intelligent equipments, the appearance structure of collector coincides with the appearance interface of measuring tool itself.

Taking the intelligent safety fence as an example, an intelligent electronic fence system with attitude detection and safety early warning is developed. Based on acceleration analysis and BLE broadcasting principle, the system mainly realizes two functions:

(1) Based on the violent shaking of the fence or the fence gap phenomenon caused by the personnel's crossing action, the feature extraction can be completed and the irregular intrusion behavior can be correctly identified; When the fence falls, give instructions to the field personnel, remind them to restore the fence in time, and realize background data recording by communicating with the intelligent control robot.

(2) When it is detected that the personnel information near the fence does not conform to the recorded samples in the database, a warning is sent back by the intelligent control robot to ensure the safety of on-site construction operations.

Hardware of intelligent electronic fence system mainly includes ST series master controller, attitude sensor MPU6050, GPS module, Bluetooth module, Wifi module and power supply module, which are modularized and installed in the upper left corner of fence.

The main control board sets a sampling period of 0.1s, samples and filters the original data collected by the attitude sensor, establishes an attitude calculation method, and calculates the triaxial acceleration signal to reflect whether the fence is in a dumping, erecting or tilting state. After field test and debugging, it can be judged that the fence is in action at this time if the SVM is larger than 2g in five consecutive sampling periods. If the triaxial angles are inconsistent in 10 sampling periods after dumping, an alarm signal will be sent to the intelligent control robot through Wifi.

The intelligent electronic fence body can be equipped with BLE module, and the personnel identification function can be realized by scanning the BLE broadcast signal of the intelligent safety
helmet. When a person approaches the fence for 1~2m, the intelligent electronic fence BLE module discriminates the information of the person every 10s, and does not handle it when the identity of the compared person meets the site safety conditions; When the characteristic information is found to be unrecorded, the audible and visual alarm is realized by transmitting it back to the intelligent control robot.

3.4. Violation recognition based on safety early warning system
According to the functions based on intelligent equipments, the expert model for violation identification is designed as follows:

(1) Establish the early warning model of safety state of insulated ladder based on inclination angle, supporting action and station on the ladder, and realize the functions of early warning of height exceeding limit, warning of inclination angle greater than 60, warning of irregular hand support, data interaction with operation robot, etc.

(2) Set the locking state and unlocking state according to the tightness and opening and closing state of the protective earth. When in a locked state, it is not allowed to move at will; Monitoring of grounding performance of grounding wire is realized by infrared correlation device, so as to ensure that the protective earth is firmly contacted with copper bar and no grounding wire is broken.

(3) According to the measured values of charged bodies and obstacles, realize early warning of interference between skip and lifting arm and obstacles and early warning of identification of charged hazards.

(4) In early warning, the intelligent robot has the function of video retrieval, which can intercept the video for several minutes before and after this moment and automatically upload it to the server for storage for staff to inquire.

After obtaining the above violation information, an expert system of intelligent diagnosis workflow is established in the background. Using the data collected during the experiment and through machine learning and training, the expert model of three-dimensional safety behavior early warning and the expert model of maintenance quality control with fidelity and traceability of digital quality control tools are established, and the digital meta-process of power maintenance whole link process supervision is optimized. On the one hand, it can provide decision support for new maintenance planning based on historical defect data, hidden danger data, non-standard items and regular maintenance plans; On the other hand, according to the working stage, it can be judged whether the current working condition is compliant, whether the data is qualified, and whether the process is omitted or mistakenly done. On-site safety control robots can be used as carriers to issue alarm instructions to remind on-site workers to prevent illegal operations such as misoperation and mistaken interval.

3.5. Communication Fusion Technology Based on Heterogeneous Data Model of Power Intelligent Maintenance Tools
The robot is equipped with an industrial communication gateway based on the Internet of Things, which hierarchically processes IOT field data from different sources and different protocols to achieve edge computing performance. Firstly, the identity information, sampling information and authority information related to different types of data, such as characters, texts, numerical values, logics, dates, etc., are subjected to attribute normalization conversion. After feature extraction, the association degree is analyzed by hierarchical clustering, and then the calculation is carried out in attribute merging and target alignment, so as to realize the collaborative data collection, transmission and analysis between the power intelligent maintenance tool and the management and control system.

3.6. Management and Control Technology Based on Mobile Edge Computing
Mobile edge computing technology can sink massive data and computing resources, and is suitable for low response delay and computation-intensive operations. The intelligent management and control robot developed in this paper is equipped with security transmission chip, RFID, MCU master
controller, positioning module and transmission module in the terminal detection device to form an edge computing integrated system, which can access and transmit data, identify the status of detection equipment and perform detection steps on the terminal network management side, and realize the closed-loop processing of local real-time diagnosis, greatly improving the channel utilization rate and effectively reducing the power loss. Combined with Lyapunov optimization algorithm, the decision of local information and calculation unloading is optimized, and the high reliable transmission calculation performance is maintained [7-8].

![Architecture of Mobile Edge Computing](image)

**Fig 3. Architecture of Mobile Edge Computing**

The edge computing software and hardware architecture can support the large-capacity data storage function, provide Python, C++ language environment, support the application in TensorFlow, Caffe and other machine learning platforms, provide a variety of data interfaces, stably realize the device interaction between the robot and each intelligent equipment communication unit, and have the characteristics of strong portability and natural networking [9-11]. Configure protocol conversion service and send it to the platform by using IEC61850 protocol; The information security service module is used to distinguish the information management area, so that the station service module, robot server, measurement and control unit, etc. can be safely isolated from the power monitoring system, and the connection application with PMS, OMS system, etc. is strengthened on the premise of ensuring the security performance of network information. The control technology architecture of mobile edge computing is shown in Figure 3.

4. Engineering application
In May 2021, the layout and test tasks were carried out in 220kV Cuiping Substation. During the experiment, 22 kinds of work violation behaviors and 8 kinds of abnormal device operation behaviors were artificially set, and the robot completed 28 kinds of specified analysis and alarm tasks, with a recognition rate of 93.3%; In 450 tests, the sensor parameters and accidents were correctly performed 397 times, and the accuracy rate reached 88.22%. Test data is shown in table 1, which can be viewed by multiple terminals.
Tab1. Recognition rate in test

| Items | Indicators | Number of tests | Identification times | Success rate |
|-------|------------|----------------|----------------------|--------------|
| Insulated Ladder | Irregular support | 30 | 28 | 93.33% |
| | Exceeding the maximum limit | 30 | 27 | 90.00% |
| | Excessive load | 30 | 29 | 96.67% |
| Security fence (Horizontal dumping angle) | 0-70° | 30 | 29 | 96.67% |
| | 70°-80° | 30 | 21 | 70.00% |
| | 80°-90° | 30 | 30 | 100.00% |
| Distance of the swinging hopper and live wire | 3-6m | 30 | 27 | 90.00% |
| | 6-10m | 30 | 18 | 60.00% |
| | ≥10m | 30 | 30 | 100.00% |
| Protective Earth | Insufficient clamping force | 30 | 27 | 90.00% |
| | loose contact; broken strand | 30 | 29 | 96.67% |
| Safety Helmet | Associated person information | 30 | 24 | 80.00% |
| Experimental equipment | Correct judgment | 30 | 27 | 90.00% |
| Background video positioning | Violation behavior capture | 30 | 23 | 76.67% |
| Total | - | 450 | 397 | 88.22% |

Man-machine interaction interface can check the data such as violation alarm information, safety measure discrimination, personnel registration, etc. The system interface is shown in Figure 4.

![Human-computer interaction interface](image)

During debugging, the following problems were encountered:

1. The video surveillance screen is stuck and interrupted. It is found that the video stream code rate and audio stream code rate are set, and the CPU frequency of industrial computer is too low. After the software is started, the CPU occupancy rate is 100%. The solution is to change the parameter setting of video stream processing and replace the industrial computer with higher configuration.
2. The signal of gateway is unstable, and the transmission data is dropped, which can be repaired by modifying the program settings.

Data can be uploaded to the cloud terminal in real time by controlling the industrial computer, 5G gateway and voice power amplifier module. The 5G gateway can modify the password by programming the input and output of the network port according to the requirements.
5. Conclusion
In this project, developed an Full-Link Management Intellectual Inspection Robot. It integrates new generation communication and information technologies such as mechatronics, multi-sensor fusion and diagnosis technology, wireless communication, edge computing, etc., has the characteristics of strong anti-interference, active safety early warning, strong information fusion ability, etc. It performs well in actual early warning and control work, and fully meets the business requirements such as intelligent human-computer interaction in the process of substation maintenance, and has broad prospects for popularization and application.

Acknowledgments
This work was financially supported by Science Project Fund of State Grid Zhejiang Electric Power Company.

References:
[1] Yang Xudong, Huang Yuzhu, Li Jigang, etc. Research Status Review of Robots Applied in Substations for Equipment Inspection[J]. Shandong Electric Power, 2015, 42(001):30-34.
[2] PENG Xiangyang, JIN Liang, WANG Ke, etc. Design and Application of Robot Inspection System in Substation[J]. Electric Power, 2018.51(2):82-89.
[3] Huang Shan, Wu Zhensheng, Ren Zhigang, etc. Review of electric power intelligent inspection robot[J]. Electrical Measurement & Instrumentation, 2018, 57(2):26-38.
[4] Wang Yuli. Research on Power Safety Instrument System Based on Internet of Things Technology[J]. Computer Knowledge and Technology, 2018, 014(006):36-37.
[5] Li Qiang. Research on Mobile Application Management of Power Safety Tools Based on Internet of Things Technology[J]. Electric Power System Equipment, 2019, 000(017):103-104.
[6] XIONG Ke, ZHANG Ruichen, WANG Rui, etc. 5G-Enabled Electricity Internet of Things: the Network Architecture and Key Technologies[J]. Electric Power, 2021, 54(3):10.
[7] Jiang Fan. Research on Intelligent Patrol Device Based on Mobile Edge Computing[J]. Technology Innovation and Application, 2019.(32):19-20.
[8] ZHOU Zhenyu, CHEN Yapeng, PAN Chao, etc. Ultra-reliable and Low-latency Mobile Edge Computing Technology for Intelligent Power Inspection[J]. High Voltage Engineering, 2020(6):1895-1902.
[9] ZHANG Wei, LIANG Junbin, QIN Jian. A Remote Centralized Control System of Substation Robot Inspection Based on MAS[J]. Electric Power Information and Communication Technology, 2020, 18(12):9-16.
[10] JIANG Yi, LIU Zhengyang, WANG Wenrui, etc. Research on multi-state monitoring system of substation equipment based on edge-cloud collaboration[J]. Power System Protection and Control, 2021, 49(06):138-144.
[11] TANG Biao, LI Ting, LI Bo, etc. Analysis and display of intelligent deployment and control data in substations based on edge computing[J]. Electrotechnical Application, 2021(2):6.