Exploration of the Development and Technical Features of Intelligent Inspection Robots

Yan Hai Li[1], Zhi Hui Chang[2], Yong Shan Ou[2], Yi Chen[3], Liu Yi Yu [3], Ji Qing Tan[4], Xiang Yu Liu[4], Yan Zuo Chang [5] *

[1] Department of Mechanical and Electrical Engineering, Mechanical Design Manufacture and Automation, Guangdong University of Petrochemical Technology, Maoming, Guangdong 525000, China

[2] Department of Electronic Information Engineering, Electronic Information Science and Technology major, Guangdong University of Petrochemical Technology, Maoming, Guangdong 525000, China

[3] School of Energy and Power Engineering, Process Equipment and Control Engineering major, Guangdong University of Petrochemical Technology, Maoming, Guangdong 525000, China

[4] School of Energy and Power Engineering, Energy and Power Engineering major, Guangdong University of Petrochemical Technology, Maoming, Guangdong 525000, China

[5] Guangdong Provincial Key Laboratory of Petrochemical Equipment Fault Diagnosis，School of Energy and Power Engineering, Guangdong University of Petrochemical Technology, Maoming, Guangdong 525000, China

*Corresponding author: cy14767703430@outlook.com

Abstract— With the development and advancement of The Times, industrial intelligence has flourished, and the emergence of inspection robots has made significant contributions to the inspection methods of the working environment in many production enterprises. Many enterprises have adopted inspection robots instead of manual inspection, which plays a significant role in achieving industrial chain upgrading and transformation. This paper compares the development trends of inspection robots at home and abroad, studies the motion structures and countermeasures of different inspection robots in different environments, analyzes the technical characteristics and advantages of inspection robots, makes corresponding measures and solutions based on the current industry situation, and explores the innovation and development trends of inspection robots in the future.

I. INTRODUCTION

With the flourishing of robotics, we are entering a new era of full intelligence. Intelligent robots, with their outstanding performance, precise control and powerful learning ability, are gradually penetrating into all areas of production and life. These robots not only produce a wide variety of types to meet the needs of different industries and scenarios, but also greatly improve work efficiency, reduce labor costs, and significantly enhance safety and reliability. At the same time, intelligent robots are produced on a large scale and are important equipment for realizing the digitalization, networking and intelligence of industrial production. Their research and development, manufacturing and application are also important indicators[1] of a country's level of scientific and technological innovation and high-end manufacturing.

Inspection is an important means to ensure the safety of production, operation or service processes. In the daily management of all kinds of facilities, equipment, and even the natural environment, inspection can detect and eliminate potential safety hazards in a timely manner, effectively curb the occurrence of safety accidents, and ensure the safety[2] of people's lives and property. Secondly, through regular inspections, one can understand

the operation status of equipment and facilities, carry out timely maintenance and upkeep, extend their service life, ensure that everything operates in order, and at the same time respond quickly to abnormal situations, reduce losses, and improve the safety and stability of the overall operation.

At present, traditional manual inspection is the main form of inspection in domestic enterprises, but manual inspection cannot guarantee that the inspectors are in place and there are many problems[3]. Manual inspection is time-consuming and labor-intensive, and is prone to incomplete or incomplete inspections due to fatigue and negligence. In addition, environmental factors such as bad weather and complex terrain can also pose safety hazards[4] to inspectors. Moreover, the data recording and processing of manual inspection are often subjective and inaccurate, making it difficult to ensure the objectivity and reliability[5] of the inspection results.

Nowadays, automated and intelligent inspection methods are gradually becoming a trend. Intelligent inspection systems connect to devices such as sensors and cameras to monitor[6] the status of equipment in real time, collect operational data such as temperature, pressure, vibration, etc., process and analyze[7] the data through software systems to identify potential safety hazards and faults, and generate inspection reports for managers to refer[8] to. In addition, the intelligent inspection system can automate inspection tasks, significantly reducing labor costs and time consumption, and significantly improving work efficiency[9]. Among them, intelligent inspection robots have significant advantages in improving inspection efficiency, precise detection, ensuring personnel safety, reducing labor costs, real-time data transmission and decision support, as well as autonomous learning and optimization, and have become a relatively reliable inspection method in today's society.

Intelligent inspection robots are highly flexible and adaptable in technology, capable of handling a wide range of complex and variable inspection tasks[10]. Meanwhile, advanced technologies such as communication technology, artificial intelligence, Internet of Things, and hybrid cloud are widely applied in various fields, providing technical support[11] for the development of intelligent inspection robots. As a result, from fire warning[12] to building troubleshooting[13], from security monitoring[14] to space operation and maintenance[15] , intelligent inspection robots are gradually replacing traditional manual inspection methods with their unique advantages. This trend of intelligence has not only driven technological advancements in intelligent inspection robots, but also injected new vitality into the development of modern industry.

II. TRENDS IN THE DEVELOPMENT OF INSPECTION ROBOTS

2.1 Trends in Inspection Robots Abroad

Research and application of inspection robots abroad started earlier than in China. The first industrial robot[16] was developed by American Joseph Engelberger in 1959 using the patent technology authorized by George Devol in 1954. In other different fields, inspection robots have also been gradually applied abroad. However, in the power industry, the research and application of intelligent inspection robots are most mature. As early as 1980, inspection robots were already being used abroad to detect[17] heat-induced defects in substation equipment. In the 1990s, Tokyo Electric Power Company and Mitsubishi Corporation of Japan jointly developed substation inspection robots, using infrared thermal imagers and digital image acquisition devices to obtain information[18] within substations; In 2008, the University of Sao Paulo in Brazil developed a mobile inspection robot for temperature monitoring inside substations, which is small in size and weight and easy to operate. The infrared thermal imager moves[19] along a high-altitude track set up above the substation. As a result, the development and research of inspection robots abroad have been constantly updated and improved, from the early two computers controlling one simple robot to the current advanced robot[20]. In the 21st century, inspection robot technology abroad has now reached the level[21] of commercial industrialization in areas such as security inspection, home services, and power inspection.

2.2 Development of inspection robots in China

Compared with the development of inspection robots in foreign countries, China's research on intelligent inspection robots started relatively late, but has developed very rapidly. The state has a lot of policy support in this field. In recent years, the state has vigorously implemented automated and mechanized working methods, and inspection robot technology has developed rapidly in China. This has led to the design and development of low-cost, efficient and reliable intelligent inspection robots, which have been widely used in inspection and monitoring, thus better replacing manual inspection methods. The Ministry of Industry and Information Technology's "Notice on the 14th Five-Year Plan for the Development of the Robot Industry" points out that "in the face of new situations and new requirements, the next five years and beyond will be a strategic opportunity period for China's robot industry to achieve self-reliance and leapfrog development." We must seize the opportunities, face the challenges, accelerate the resolution of problems such as insufficient technological accumulation, weak industrial

foundation and lack of high-end supply, and push the robot industry towards the medium-high[22] end.

Research on inspection robots in China began with substation inspection robots in Shandong Province in 1999. The idea of using mobile robot technology for equipment inspection in substations was first proposed in 2001, and the first domestic product prototype was developed and applied in the 500kV inspection operation[23] of Changqing Substation in October 2005. After years of research, intelligent inspection robots have gradually achieved certain development results, especially in the application[24] of intelligent inspection robots in substations of the power industry. An active disturbance rejection control (ADRC) architecture[25] based on data-driven method compensation is proposed, for example, in response to the problem that inaccurate control input matrices can affect control performance in the ADRC system of substation inspection robots. A lidar-based inspection robot system was studied in response to the complex environment of substations, the high intensity and low efficiency of manual inspection. The environment map was established using the laser Simultaneous Localization and Mapping (SLAM) algorithm, and real-time localization was carried out using the Adaptive Monte Carlo localization (AMCL) algorithm in combination with laser and odometer data. For the substation environment, inspection coordinates and key points in the path were marked on the map, and global path planning and point-to-point navigation algorithms[26] were designed.

Nowadays, industrial development is rapid and society is gradually entering the intelligent era. Artificial intelligence technology exists in the production equipment of numerous manufacturing enterprises, with a wide variety of types and large demands. It is also used in a wide range of different fields, such as the application of inspection robots in utility tunnels, the research[28] and application[27] of intelligent inspection robots in offshore oil fields, and the study[29] of suspended track-type intelligent inspection robots. To use the intelligent inspection robot efficiently and safely, we need to develop a complete control system that enables it to navigate through its positioning system, automatically collect information, and detect problem points. Monitor the inspection robot via wireless network, process the collected images, automatically alarm abnormal points, automatically notify daily inspectors to go to the occurrence site for confirmation and prompt handling, thereby achieving efficient and reliable intelligent inspection results.

Looking at the development status of domestic intelligent inspection robots, intelligent networking is a good carrier. Intelligent inspection robots achieve

intelligence through the Internet and their own computing. For example, before working, intelligent inspection robots need to know the status of nearby devices through the Internet, and some devices need to be inspected with focus. When faults are detected, the information is integrated and processed through the Internet and finally sent to robot terminals or human terminals with other functions. Then proceed to the next step. The connected system of the intelligent inspection robot is like the human body system, in which the intelligent inspection robot plays the role of the "nerve center", and the Internet and other mobile terminals are the "blood

vessels" of the "nerve center", and the "blood" carried in it continuously provides "nutrition" for the intelligent inspection robot to work efficiently and accurately. Networking is a product of the development of the Internet of Things and a concrete manifestation of it. From a broader perspective, connectivity will drive the upgrading and transformation of the robotics industry[30] and become the most promising development trend today.

III. DESIGN OF THE MOTION STRUCTURE OF INSPECTION ROBOTS

3.1 Ground inspection robot

3.1.1 Wheeled inspection robot

A wheeled inspection robot is an automated robot that uses wheels as a means of movement and is primarily used for monitoring and inspecting various facilities and infrastructure. The advantage of the wheeled inspection robot over other robots lies in its simple structure, high flexibility, fast movement speed, wide range of movement, high degree of autonomy, and suitability for flat and open roads[31]. With the acceleration of urbanization, traffic tunnels have become an important part of the modern transportation network. However, due to the complex and changeable internal environment of tunnels, traditional manual inspection methods are difficult to meet the requirements. Therefore, Chen Guocui et al. have proposed a new type of tunnel wheeled inspection robot. The wheeled inspection robot uses a multi-wheel independent drive walking mechanism to achieve all-round flexible movement, and it ensures continuous contact between the wheel-ground contact surface and the tunnel profile through active suspension technology, guaranteeing the robot's ability[32] to pass. Likewise, for the special working environment in coal mines and coal washing plants, Li Pengcheng et al. have designed a wheeled drive inspection robot suitable for narrow Spaces. This robot uses two-wheel differential drive and is small in size, which can ensure smooth cornering and flexible passage through narrow Spaces[33]. The wheeled chassis structure

of the wheeled inspection robot produced by CITIC Heavy Industries Kaicheng Intelligent Equipment Co., Ltd. not only has the basic functions of the above wheeled inspection robot, but also has excellent climbing and obstacle-crossing capabilities[34] .

There is also a wheel-legged inspection robot based on the wheel-mounted inspection robot, which can work flexibly in various terrains. The detachable wheel-legged quadruped inspection robot designed by Dou Yuhuan et al. takes advantage of the wheel-legged inspection robot. It can flexibly switch operation modes according to the actual environment of the mine and also improves the stability[35] of the robot. In addition, the McNam wheel inspection robot is also widely used. TheMcNam wheel inspection robot is an omnidirectional mobile robot platform based on the McNam wheel. Each wheel is equipped with a 45-degree bevel roller, which allows the robot to move and rotate freely. Some designers have created the McNam wheel inspection robot, which takes advantage of the high[36] degree of freedom of the McNam wheel. This McNam wheel inspection robot has the ability[37] to move in all directions and can move and rotate freely in narrow Spaces or environments with dense obstacles. Therefore, it is often used in industrial environments where mechanical equipment, pipelines, etc. need to be inspected frequently.

3.1.2 Crawler-type inspection robots

A tracked inspection robot is an automatic or remote-controlled robot with a tracked drive system, often used for inspection tasks in complex or harsh terrain. Tracked patrol robots have a significant advantage over wheeled patrol robots. Tracked patrol robots can move stably on uneven, rough or soft surfaces such as muddy, sandy, snowy or stony ground. The tracks provide the robot with a large ground contact area, reducing the pressure per unit area, allowing the robot to move on soft ground without getting stuck. The multimodal intelligent tracked inspection robot designed by Li Minghao and others takes advantage of the tracked inspection robot, with a tracked chassis that enhances the inspection robot's ability[38] to handle complex road conditions. Tracked inspection robots are often equipped with multi-functional accessories such as robotic arms, cameras, sensors, etc., and can perform various tasks such as inspection, monitoring, grasping, and repair. The tracked inspection robot with an auxiliary wheel swing arm, designed by An Zhiguo et al., is simpler in structure, smaller in size and lighter in weight compared to previous tracked inspection robots. It has better obstacle-crossing and grasping capabilities and can perform multiple tasks[39] simultaneously.

The chassis tracks in the tracked inspection robot are an important advantage of this robot. The tracks are placed parallel to the ground, providing a wider support base surface. Therefore, compared with wheeled inspection robots, the tracked inspection robot can easily climb slopes or cross obstacles such as stones, broken wood, etc., and it can also remain stable on steeper slopes or unstable ground. For example, the current oil and gas pipeline robots have problems such as weak adaptability to oil and gas pipelines and poor climbing ability. Yu Jiuyang et al. have proposed a tracked oil and gas pipeline inspection robot that can change diameter. The inspection robot is mainly used in chemical pressure pipelines, crude oil, refined oil and natural gas transportation pipelines. It can perform intelligent inspection functions on special equipment such as pressure vessels and pressure pipelines in chemical equipment in industries such as chemical engineering, oil and gas, and nuclear power. It can also climb 45-degree and 90-degree slopes[40] while bearing its own weight. Tracked inspection robots typically consume more maintenance and energy than wheeled ones because of their structure and drive mode. But tracked patrol robots can reach hard-to-reach areas, and the value of performing tasks often outweighs the additional cost. As Han Long etal. designed, the tunnel crawler inspection robot is used in narrow tunnels that are difficult for workers to access. It can not only move steadily within the tunnels but also transmit real-time information[41] about the tunnels.

3.2 Underwater inspection robot

Underwater inspection robots are a type of robot that can independently or remotely perform inspection, detection, maintenance and other operations in underwater environments. They are widely used in the fields of underwater facility inspection, water quality monitoring, Marine biological research, and diving rescue assistance. In response to the complex underwater environment, Favor Oluwatobi Adetunji et al. delved into the challenges associated with navigation and maneuverability in remotely operated ROV (ROV) teleoperation and introduced an underwater digital twin (DT) system aimed at enhancing underwater teleoperation, enabling autonomous navigation, and supporting system monitoring. And through simulation to facilitate system testing, the situational awareness of remote operators was enhanced and their workload[42] was reduced. To address the energy consumption problem, Fu experimentally established the correspondence between different swimming postures of robotic fish and energy consumption in the flow field environment, and used reinforcement learning algorithms to optimize the swimming postures with the least energy consumption of fish in the flow field, achieving energy savings[43] in

group movement. Regarding how to obtain underwater images without dehydration and how to analyze wear through images, Li Yonglong et al. developed a novel underwater inspection system, UIS-1, and designed an integrated component for the underwater robot, which partially removed silt and obtained images of the concrete surface of the still water pool plate at the desired position; Secondly, an image algorithm was proposed to obtain the aggregated exposure rate for quantitative wear analysis[44] .

3.3 Aerial Inspection Robot

An aerial inspection robot is typically an unmanned aerial vehicle equipped with high-definition cameras and advanced sensors. They can fly autonomously and perform environmental analysis and data collection through built-in computer systems and artificial intelligence algorithms. These robots are primarily used for quick and efficient inspections of every corner of the city. To alleviate the problems of poor route planning and low cruise efficiency of unmanned aerial vehicle (UAV) power inspection, and to avoid the threat of unreliable paths, Chang An et al. proposed research methods for intelligent route planning and autonomous inspection of UAV power inspection, which improved the autonomous inspection effect, route planning effect and cruise efficiency[45] of UAVs. Zhuo Haoze et al. proposed a drone pose estimation method based on point-line feature fusion in the transmission line scene, which solved the problem of poor robustness of traditional drone visual odometry, enabling drones to efficiently extract point and line features in infrared images and have stronger robustness[46] in weak texture and sudden light changes environments.

IV.   FEATURES OF ROBOTICS TECHNOLOGY

4.1 Autonomous Path planning

Autonomous path planning is the automatic planning of an optimal or suboptimal path from the starting point to the destination point by a robot or unmanned system without external guidance based on its own sensor data and preset algorithms. It is a core component of robotics technology.

The various algorithms that enable robots to achieve autonomous path planning each have their own advantages, but there are still some areas that need improvement. For example, the RRT algorithm requires a lot of iterations to find the path, so the time cost of the entire process is relatively high. Yu Qiang et al. conducted a study on path planning based on the MI-RRT^ (*) (Modified Informed RRT^ (*)) algorithm. By introducing greedy sampling and adaptive step size methods, they improved the convergence rate of the algorithm and reduced the path

generation time[47] . Path planning for mobile robots in complex environments faces problems such as insensitivity to the environment, low efficiency, and poor path quality of the fast-extended RRT algorithm. In 2023, a CERRT algorithm was proposed by scholars, and simulation results showed that CERRT performed better than RRT and RRV algorithms[48] in complex environments such as mazes and narrow passages. In the factory sector, the increasing labor costs make it difficult for factories to recruit employees to perform manual operations. Zhang Yu et al. proposed a GFS RRT^ (*) -SMART algorithm for global path planning and a deep reinforcement learning hybrid behavior evaluation (MAC) algorithm for obstacle avoidance decisions in local obstacle avoidance, enhancing the robot's performance[49] in sharp turns. In some cases, the computational cost of the A* algorithm can be very high. And factory safety checks are crucial for maintaining a safe production environment. At present, inspections are mainly carried out manually on a regular basis, resulting in low efficiency and heavy workload. Some scholars have proposed A hybrid path planning algorithm that combines the A-star algorithm and the time elastic band algorithm to address the problem of path planning getting stuck in local optimum in complex environments and improve the detection efficiency[50] of robots. Some scholars have proposed an ASL-DWA (A Star Leading Dynamic Window Approach) algorithm compared to the traditional A-star algorithm, which searches for more nodes, resulting in broken paths that cannot.avoid local unknown obstacles. And a mechanism was designed to adaptively adjust the coefficient based on the distance between the robot and the target point, thus achieving ASL-DWA. Compared with traditional algorithms, the ASL-DWA algorithm can meet the path planning requirements[51] of mobile robots in indoor environments.

4.2 Visual image recognition

Visual image recognition is an artificial intelligence technology that enables computers to "see" and understand visual data by imitating human visual perception. At present, visual image recognition technology still faces many challenges such as complex backgrounds, lighting and scale variations, and real-time performance. In 2010, Wen Feng et al. studied SLAM algorithms for monocular vision by fusing visual information with odometry information using extended Kalman filters to improve the accuracy of robot positioning and mapping. [52]In addition, visual object detection and segmentation have been an important research area for autonomous driving environment perception, but mainstream object detection and segmentation algorithms have problems such as low detection accuracy and poor mask segmentation quality for multi-object detection and segmentation in complex traffic

scenarios. Some scholars have improved the Mask R-CNN by replacing the backbone network ResNet with the ResNext network with group convolution, further enhancing the model's feature extraction ability.[53]

Wildfires have a negative impact on forest biodiversity and human life. It spreads so fast that early detection of smoke and fire plays a crucial role in improving the efficiency of firefighting operations, but the different shapes, sizes, and colors of smoke and flames make their detection a challenging task. In 2024, scholars employed the latest YOLO algorithm for detecting and locating smoke and wildfires in ground and aerial images. The YOLOV7X model outperformed the baseline model in detecting both smoke and wildfires, while the YOLOV8S achieved[54] some success in identifying and locating wildfire smoke alone. The development of educational robots holds great promise in the field of education, as they can interact with students in learning environments and provide personalized educational support for students. However, object detection in complex environments remains challenging because classrooms or learning scenarios involve various objects, backgrounds, and lighting conditions. In 2024, scholars proposed a brain-inspired heuristic approach for educational robot object detection that integrates Faster R-CNN, YOLOv3, and semi-supervised learning to improve the accuracy and efficiency[55] of object detection in educational robot systems.

4.3 Communication Control System

4.3.1 Remote control and monitoring

Remote control and monitoring refers to the technology of operating, managing, and monitoring remote equipment, systems, or processes through a network or other means of communication, allowing users to control and monitor the target object away from the actual operation site. Although significant progress has been made in remote control and monitoring technology, there are still certain limitations such as security issues, real-time requirements, data processing and analysis, etc.

In response to the complex information and unstable collaboration in multi-robot remote monitoring systems, Liu Xin et al. proposed a hierarchical architecture for shared control systems based on multi-Agent technology, and designed a hybrid Agent architecture for the characteristics of teleoperation systems. The practicability and effectiveness[56] of the hybrid Agent architecture were verified through experiments.

For the special application environment of the substation, there are certain requirements for the operational reliability, parking positioning accuracy and anti-interference ability of the inspection robot. Zhu

Xingke et al. designed a motion control system for a substation inspection robot. Through magnetic trajectory guidance and RFID positioning, as well as the technology of differential speed of two drive wheels and follow-up of two swivel wheels, the posture and position of the robot body were determined respectively, and motion control instructions were executed to meet the application requirements[57] of the substation inspection robot. Sun Dihua et al. proposed a HSIC-Smith control algorithm to improve the dynamic performance of the teleoperation system of the inspection trolley in response to the shortcomings of the current control schemes for the network delay variation problem, such as the contradiction between stability and operability, excessive reliance on the model accuracy of the controlled object and poor anti-interference ability. Compared with the conventional PID-Smith pre-estimation method, this algorithm enables rapid and accurate teleoperation control of the inspection trolley system under the condition of network delay variation, and has strong adaptability[58] to the change of network delay.

4.3.2 Fault Diagnosis and Alarm

In robotics technology, fault diagnosis and alarm is a process that involves monitoring the operational status of robots, detecting and identifying potential faults or abnormal situations, and issuing alarm signals to enable timely measures to be taken for handling. Although fault diagnosis and alarm technology is widely used in the field of robotics, it still faces challenges due to the limitations of sensor technology, the complexity of fault models, and the adaptability of diagnostic algorithms. Zhao et al. obtained estimates close to the real model state through UKF filtering to determine the type of sensor fault. Experimental comparisons with traditional FSMM methods show that this method can effectively determine the fault types of individual or combined sensors in mobile robots and significantly improve diagnostic accuracy[59]. By placing various corresponding sensors on the medical devices that needed to be monitored, Huangfu Dejun et al. achieved pre-scheduling of medical device failures and enhanced emergency response capabilities. He developed a medical equipment inspection monitoring and alarm system to improve the traditional medical equipment supervision system and enhance the intelligent inspection effect[60] of medical equipment.

V. CONCLUSION

With the continuous improvement of safety management standards in modern industry and the rapid development of science and technology, intelligent inspection robots, as an intelligent auxiliary tool, are gradually becoming the backbone of safety, environmental

protection, and data-driven management. At present, intelligent inspection robots have demonstrated their unique advantages and potential in various scenarios such as pipe galleries, tunnels, and substations, but their widespread application is still insufficient and their diversified development is in urgent need of improvement. Many enterprises still rely on traditional manual inspection methods, which are not only limited by issues such as labor costs, efficiency and safety, but also difficult to meet the urgent demands of modern industry for efficiency, accuracy and intelligence. At the same time, although inspection robots on the current market have certain autonomous navigation, data collection and analysis capabilities, their adaptability, stability and intelligent decision-making capabilities still need to be enhanced in complex and changeable working environments. With the continuous maturation and integration of technologies such as artificial intelligence, the Internet of Things, and big data, intelligent inspection robots will have a much broader space for development. More innovative inspection robot products will emerge in the future, which will have stronger autonomous learning ability, higher environmental adaptability and wider application scenarios, and be able to accurately identify potential safety hazards in complex environments and achieve efficient inspection and intelligent diagnosis. Meanwhile, with the popularization of technology and the reduction of costs, intelligent inspection robots will gradually become an indispensable part of enterprise safety production and operation and maintenance management, driving the entire industry towards a more intelligent and unmanned direction. This will not only greatly enhance the production efficiency and safety of enterprises, but also contribute more to the sustainable development of society.

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