Study of Robotic Non-destructive Testing Solutions

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Abstract. In the field of pressure vessel inspection and flaw detection, the use of robots to replace manual non-destructive testing has been a research focus. In order to reduce the need for human labor and improve the efficiency of non-destructive testing, this paper analyses the issues with traditional manual non-destructive testing and introduces three robot-based non-destructive testing technologies: ultrasonic testing, magnetic leakage testing, and radiographic testing. Additionally, this paper discusses the principles of flaw detection technology and their respective application scenarios, as well as the design of the robot structure and main control system for three technologies. Therefore, it underscores and summarizes the benefits, potential issues, and challenges encountered in practical engineering. This study seeks to offer a profound understanding and dependable guidance for advancing innovations in robotic non-destructive testing methods, along with enhancing the intelligence of industrial production. In the foreseeable future, the robot-based non-destructive testing technology is anticipated to yield innovative advancements and to consistently evolve towards enhancing the intelligence of industrial production. This anticipated progress will be facilitated by relentless research in technological innovation, intelligent control systems, and practical engineering applications.

Keywords: Pressure vessel, non-destructive testing technology, wall climbing robot, automated inspection.

1. Introduction

Nowadays, pressure vessels are widely used as closed containers capable of carrying fluid medium pressure, particularly in extreme working environments such as high temperature and high pressure [1]. Regular manual quality testing is necessary to prevent explosions or leaks, which can cause immeasurable losses to society. The non-destructive testing technique is widely used in this field due to its characteristics of non-destructive testing, accurate and reliable results, and wide range of use. However, there are still some problems with non-destructive testing of pressure vessels by hand. On the one hand, non-destructive testing, as a kind of testing method based on the theoretical knowledge of light, electricity, magnetism, force, etc., To ensure the pressure vessel remains undamaged, inspectors must possess high-level professional skills, be proficient in using instruments and equipment, and strictly adhere to non-destructive testing processes and standards [2]. Additionally, due to the pressure vessel's strength, stiffness, and stability, testing can be conducted in various ways, taking into account human factors. However, the inspection process of pressure vessels can pose safety hazards due to their low strength, stiffness, and stability, as well as various human factors [3]. Therefore, it is of great research significance to explore the possibility of replacing manual non-destructive testing with robots.

Previous studies have extensively explored the performance and applicability of non-destructive testing techniques in robotic applications. Ultrasonic inspection is widely used for volumetric inspection of welds, castings and forgings due to its versatility and ability to penetrate materials. Leakage inspection, which applies magnetic fields and ferromagnetic particles to detect surface and near-surface defects, offers significant advantages. Radiographic inspection provides internal imaging of structures and is important for inspecting thick-walled parts and critical aerospace components. It is an objective method of inspection that allows for the detection of internal defects that may not be visible to the naked eye. However, despite the widespread use of these techniques in the field, integrating them into robotic systems still presents several challenges. These include the impact of factors such as complex geometries, material properties, and environmental conditions, as well as the mobility, accessibility, and sensor compatibility of the robotic platform.

In order to provide valuable insights for optimizing the design of robotic non-destructive testing schemes and inspiring automation in industrial applications, this paper will discuss and evaluate the several robot-based non-destructive testing methods and explains the testing principle and mechanical structure of three robots, along with their control method. It also compares their advantages and disadvantages and analyses their feasibility in actual engineering.

2. Ultrasonic Non-destructive Testing Robot

2.1. Ultrasonic Guided Wave Non-destructive Testing Techniques

Ultrasonic non-destructive testing technology involves the interaction of ultrasonic waves with the test object. The ultrasonic instrument emits waves with a frequency greater than 20 kHz, which propagate through the medium in a straight line. During propagation, the waves experience attenuation and scattering. If defects are detected in the object, the ultrasonic waves will change direction or acoustic characteristics, and this acoustic information will be fed back to the ultrasonic instrument for processing. This allows for the comprehensive evaluation of the object's macroscopic defects, geometric properties, organizational structure, and mechanical properties [4]. The testing technology typically involves the use of equipment such as an ultrasonic flaw detector, probe, and coupling agent. The operation method consists of placing the ultrasonic probe directly on the surface of the object to be tested. A layer of non-corrosive coupling agent is applied to the surface to optimize probe contact. Ultrasonic waves reflect on internal defects, and the shape of the echo can be analyzed to investigate the performance of the metal welding process [5].

2.2. Wall Climbing Robot Based on Ultrasonic Non-destructive Testing

The combination of ultrasonic non-destructive testing technology with a wall climbing robot has led to the successful development of a water-cooled wall wear detection robot that climbs walls through magnetic suction [6]. Figure 1 shows the design structure of the wall-climbing robot. The robot's body has two pulleys on the left and right sides, respectively, and a track equipped with permanent magnet block engagement to enable wall climbing and travelling. The robot that crawls on walls uses a rear drive mode. Two main drive wheels at the back are powered by a DC brushless motor through a worm gear. On the front side, there are ultrasonic non-destructive testing and image acquisition components. These components are driven by a DC small motor and slider to move the probe in the panning guide back and forth to find the appropriate detection point. Finally, the pneumatic part of the probe is controlled to measure the wall thickness and acquire data.

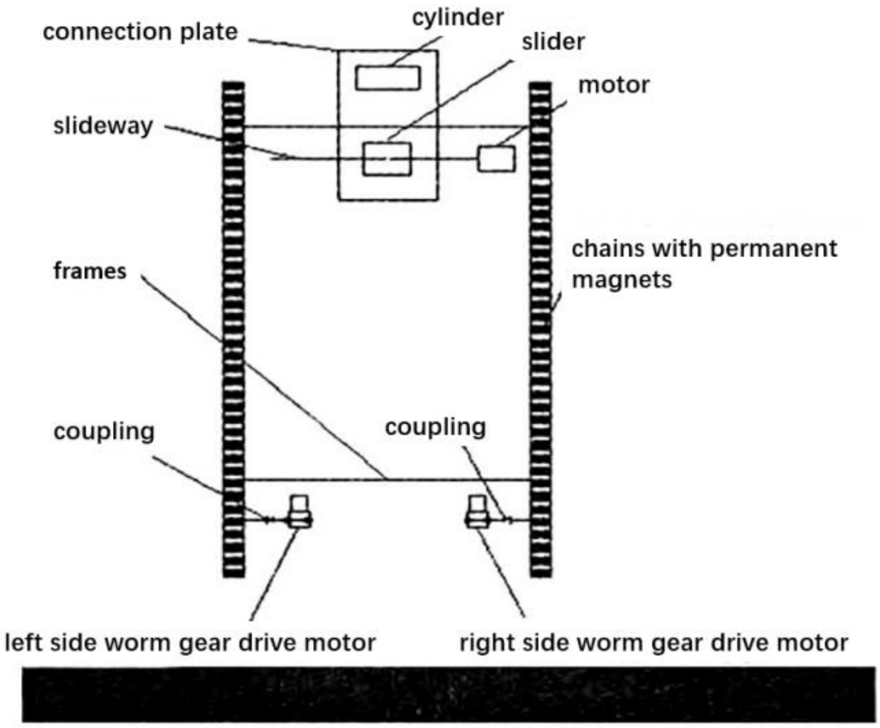

Fig. 1 Sketch of wall climbing robot structure [6]

The robot's control system is structured into upper and lower control systems, consisting of an STM32 microcontroller, motor driving circuit, sensor data receiving circuit, and human-computer interaction interface. The PC serves as the main control computer for the upper system, used for parameter initialization, task planning, state monitoring, and collecting and processing final monitoring data. The lower computer system utilizes the STM32 microcontroller as its core to control the automatic movement of the wall-climbing robot. This enables the robot to move forward, backward, and change direction, and to reach the position for ultrasonic non-destructive testing. The language used is clear, objective, and value-neutral, with a formal register and precise word choice. The text adheres to conventional structure and formatting features, including consistent citation and footnote style. The grammar, spelling, and punctuation are correct. No changes in content have been made. The wall climbing robot utilizes a fuzzy PID controller in its motion navigation to detect and adjust for lateral and angular deviations from the tracking path, improving its working efficiency. The upper and lower control systems communicate via RS232, as shown in Figure 2.

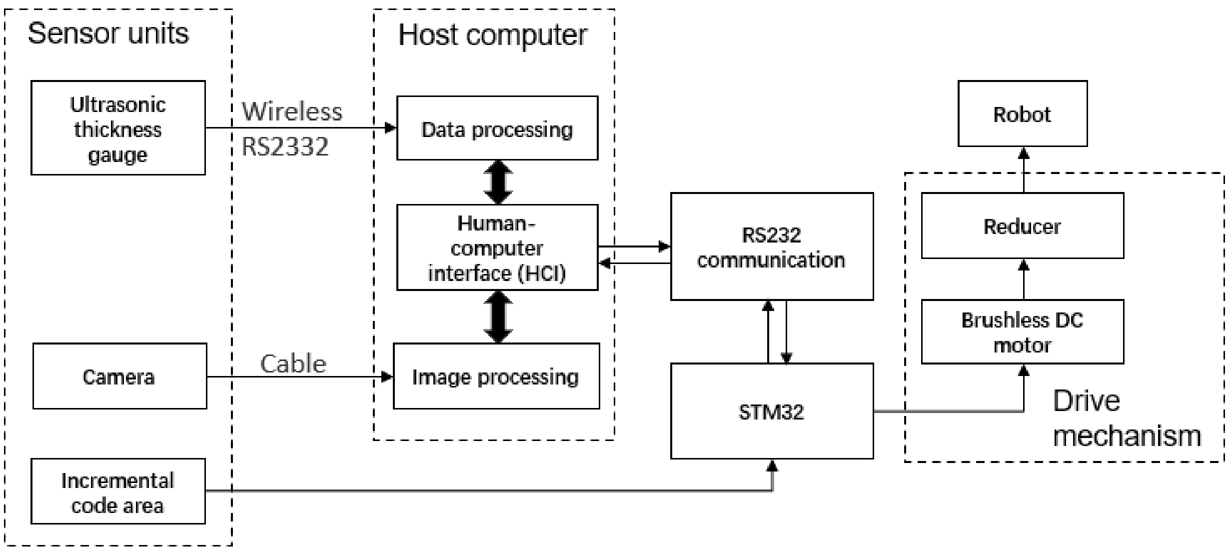

Fig. 2 Block diagram of robot control system [6]

3. Magnetic Leakage Non-destructive Testing Robot

3.1. Magnetic Leakage Non-destructive Testing Techniques

Magnetic leakage detection technology involves applying external magnetization methods to metal magnetization processing, inducing a magnetic field within the metal to be detected. If the metal surface is smooth and has no internal defects, the magnetic flux lines will pass through the metal near the surface. This method is used to detect defects in metal structures. When metal experiences corrosion, cracks, or other volumetric defects, the permeability in and around the affected area is reduced, and the magnetic susceptibility of the surrounding area leaks to the metal. Volumetric defects, such as corrosion cracks, cause a decrease in permeability in the adjacent area, and the magnetic lines of inductance around the defect leak to the outside of the metal, resulting in magnetic leakage [7]. This technology typically requires equipment such as a magnetization device and a probe (usually a magnetic field sensor used to detect magnetism leakage). Magnetic leakage detection technology is widely used in the quality inspection of storage tanks due to its advantages of high detection efficiency, high coverage, and high accuracy, making it an effective and reliable detection method [8].

3.2. Crawling Robot for Magnetic Leakage Detection of Oil Storage Tank Walls

The advancement of science and technology has led to the creation of a crawling robot designed for detecting magnetic flaws in oil storage tank walls [9]. Figure 3 displays the three-dimensional design assembly diagram. The robot uses a permanent magnetic adsorption method and has a wheel-type mobile design. Its four-wheel body is made of permanent magnetic ferromagnetic material, and the outer belt of the wheels is made of rubber material. The contact area between the wheels and the wall is increased to enhance the friction between the wall-crawling robot and the tank wall, preventing it from falling down. The robot is powered by a brushless DC motor due to its high reliability, stability, and response speed requirements. The robot's workflow is as follows: Firstly, the robot is placed on the tank wall. After calculating the optimal detection path, the robot automatically starts crawling. During the crawling process, the robot can use a fixed rotary axis and manipulator to control the position and height of the probe's end. This allows for real-time leakage detection of the tank wall during the travelling process. Ultimately, the robot can detect the tank wall at any position and store the results for analysis.

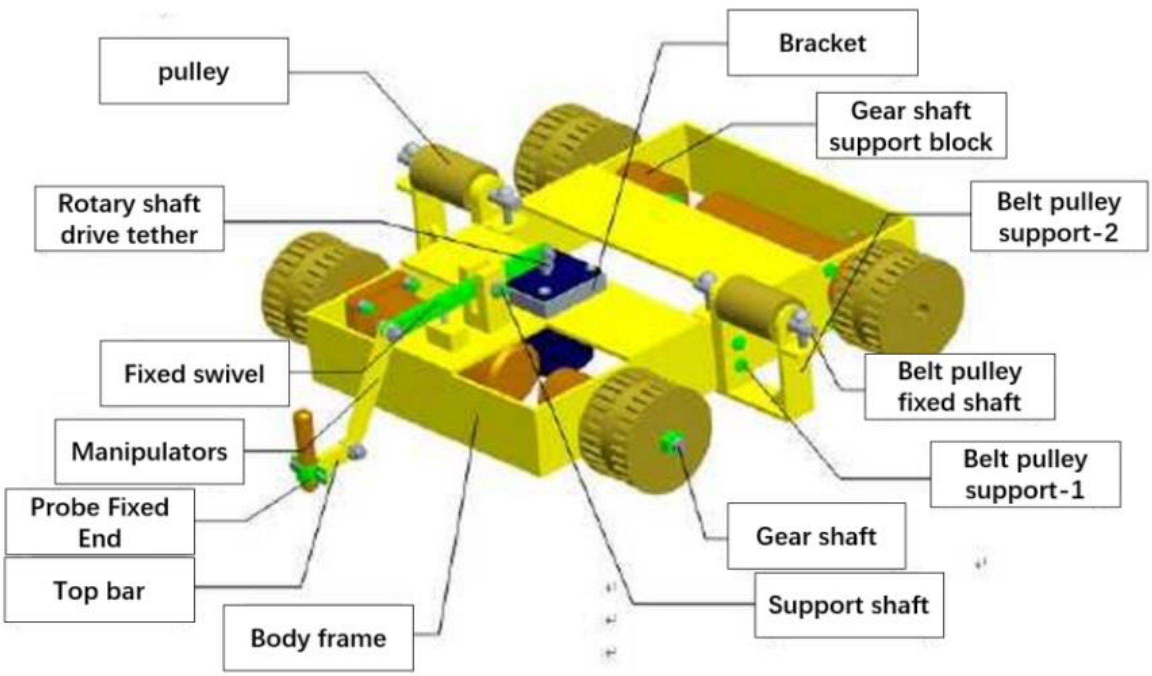

Fig. 3 3D assembly diagram of the crawling robot [9]

Figure 4 shows the control system structure of the robot. A master-slave two-level control system is used to control the wall-climbing robot operation. The PC, located at the top, exchanges data with the robot through a wireless communication module to plan tasks, monitor processes, and process data. The lower bit's data acquisition module is centered around the STM32F103ZET6, which has dual serial ports. One port is dedicated to collecting inspection data and storing it in Ferroelectric Memory (FRAM) for real-time transmission to the main controller. The other port is used for GPRS connection and data transmission, as well as the microcontroller STC12C5604AD's control module. The control module utilizes the STC12LE5604AD microcontroller as its core unit. Upon receiving a power-off or gate-close command from the core chip of the data acquisition module, the module part will execute the relevant action command operation. The power supply module in this design incorporates a rechargeable lithium battery, providing backup power supply to the main chip and communication module part to prevent data loss in the event of a power failure.

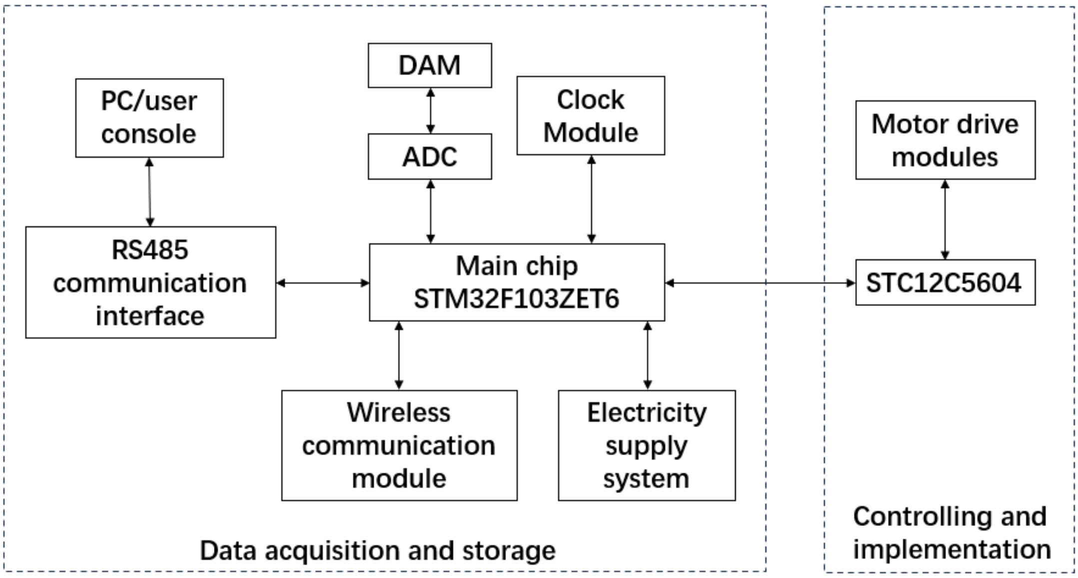

Fig. 4 Block diagram of control system [9]

4. Radiographic Non-destructive Testing Robots

4.1. Radiographic Non-destructive Testing Techniques

Non-destructive testing using rays can be divided into two types: X-ray flaw detection and γ-ray flaw detection. γ-ray flaw detection is commonly used for thick workpieces due to its high penetration ability but weak sensitivity, while X-ray testing is commonly used for pressure vessels. X-ray non-destructive testing technology involves the use of X-rays to penetrate the thickness of a material and measure its resistance coefficient. The internal defects of the material are revealed through different colors due to the varying strength of resistance emitted by the substance. It is important to note that this technology should be used objectively and without subjective evaluations. The technique of determining the location and size of internal defects in a pressure vessel involves displaying corresponding images on photographic film. This is achieved by exploiting the different colors of internal defects resulting from varying emission resistance of the material. The colors are distinguishable from the surrounding ray penetration thickness and resistance coefficient. The equipment required for this technique includes an X-ray source, image intensifier, CCD camera, digital detector, etc. The technology is primarily used to detect defects in pressure vessel weld locations. The manual process involves scaffolding being erected around the pressure vessel prior to testing. A weld developer film or digital flat panel detector is then attached around the weld, and a ray source is fixed in the middle of the tank for exposure. The resulting data is processed to obtain an image of the weld interior, which is then analyzed to determine the weld condition [10, 11].

4.2. Intelligent Robot for Weld Radiographic Inspection

Due to the complexity and low efficiency of manual non-destructive testing operations, as well as the harmful effects of X-rays on human health, some scholars have designed and studied an intelligent robot for weld ray inspection [12]. The robot uses the principle of magnetic suction adsorption and a dual-vehicle detection scheme. This allows two load-bearing trolleys to carry the ray source and the digital flat panel detector, which are attached to the surface of the pressure vessel through the magnetic force of the permanent magnets. The design of the robot is shown in Figure 5. The robot located at the ray source end functions as an autonomous walking robot, which is remotely controlled by the remote-control processing platform or walks along the designated route. On the other hand, the robot situated at the digital flat panel detector end serves as a tracking robot. Its main task is to locate the position of the robot at the ray source end and track it to ensure that the ray source and the digital flat panel detector correspond to each other on both sides of the weld seam. This ultimately enables the non-destructive testing of the weld seam. The robot's motion structure utilizes an omni-directional Meconium wheel design, enabling movement in all directions and rotation around its own axis. This design also creates a gap between the adsorption unit and surface, providing flexibility while maintaining loading capacity.

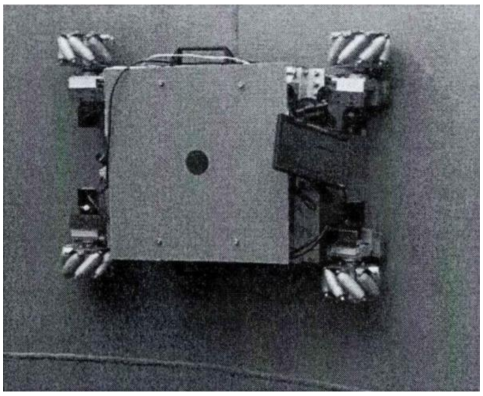

Fig. 5 Intelligent robot for radiographic inspection of welded seams [12]

The robot's detection system consists of two main parts: hardware and software. The hardware uses the PCM-9389 motherboard as the core controller and employs the principle of distributed motor control based on the CAN bus to independently move the four wheels. Additionally, the system includes peripheral devices such as trajectory sensors, attitude sensors, and wireless communication modules to ensure reliable and efficient detection. A modular approach is used in software to separate the implementation procedures of various functions from the main program. This allows the main program to call each module's function directly. The main tasks of the software system are to transmit the real-time motion status and positions of the two robots to the remote-control terminal, receive control tasks from the terminal, and control the four-way motors to enable remote control by the robot control center. The control center for the robot manages the four motors to enable remote control, tracing, or remote control and tracking functions. This ultimately achieves closed-loop control of the entire system.

5. Discussion

This paper discusses the advantages as well as the limitations of the above three inspection robots based on their working principle, mechanical design, control system, and execution logic, respectively, as follows.

Ultrasonic non-destructive testing robots: Ultrasonic non-destructive testing technology is highly efficient and can detect small defects within metal characteristics. When combined with wall climbing robot technology, they offer easy operation, high automation, and remote monitoring capabilities. However, this solution still has limitations. Ultrasonic non-destructive testing requires a clean environment and coupling agent to ensure accurate detection. This leads to higher workplace and robot operation requirements. Some metals have a strong ultrasonic weakening ability, which affects the propagation distance and detection depth, reducing sensitivity and accuracy. Wall-crawling robots are currently primarily used for detecting flat surfaces. However, their ability to detect complex curved or non-planar surfaces is limited, and their maintenance costs are high, which limits their popularity and application.

Magnetic leakage non-destructive testing robots: Magnetic leakage testing technology offers high sensitivity without surface contact. Additionally, the testing equipment is simple, lightweight, and easy to install on wall-climbing robots, which can improve the efficiency of container wall testing. However, this combination of solutions still has limitations. Due to the requirement to magnetize the material before leakage detection, materials with lower permeability will result in reduced measurement accuracy. The magnetic suction wall-climbing robot wheels are made of magnets, which inherently produce a magnetic field. This may impact leakage detection and reduce detection accuracy. Due to the principle of limiting vessel wall thickness, this technology has a greater impact on detection reliability and cannot effectively detect deep or internal defects. Therefore, it is mainly used to detect surface and near-surface defects in materials.

X-ray non-destructive testing robots have the advantage of direct observation of internal defects, detection of a wide range of thicknesses, and applicability to various materials. X-ray non-destructive testing robots have the advantage of direct observation of internal defects, detection of a wide range of thicknesses, and applicability to various materials. X-ray non-destructive testing robots have the advantage of direct observation of internal defects, detection of a wide range of thicknesses, and applicability to various materials. When combined with wall-climbing robots, they can protect personal health, save on the economic cost of detection, and improve detection efficiency. However, this solution still has limitations. Considering the technical principle of X-ray non-destructive testing, detecting defects on the surface of a workpiece is more challenging, making comprehensive flaw detection on pressure vessels unfeasible. Additionally, X-ray detection technology requires precise instruments and a smooth working environment, with higher stability requirements for robots. The robot detection program is specialized, using dual robots for inspection, and the inspection and control system is complex. Maintenance and troubleshooting work may be relatively difficult.

In general, robotic non-destructive testing technology can improve testing efficiency to a certain extent and save human resources. However, there are still many shortcomings that require continuous improvement and optimization.

6. Conclusion

This paper presents a method for non-destructive testing of pressure vessels using robots instead of human inspectors. Three types of non-destructive testing robots are introduced and analyzed, each with its own unique characteristics. The ultrasonic non-destructive testing wall-crawling robot offers advantages not only in ensuring a certain degree of measurement accuracy but also in reducing the difficulty of equipment operation and manufacturing costs, making it more feasible. The magnetic leakage non-destructive testing robot has the advantage of requiring less equipment for operation, with lower load requirements for wall-crawling robots. However, its detection accuracy is easily affected by the environment. The ray non-destructive testing robot allows for direct observation of internal damage situations with high detection accuracy. However, its operating system is complex and equipment costs are high. The nondestructive testing robot using ray technology can accurately observe internal damage, but its operating system is complex and the equipment cost is high. Overall, wall-crawling robots for non-destructive testing have significant potential in the industrial field. They can improve detection efficiency, protect operator safety, and provide effective support for product quality control. In the future, robot-based non-destructive testing technology is expected to achieve more innovative results and make continuous progress towards the intelligence of industrial production. This will be achieved through continuous research on technological innovation, intelligent control systems, and practical engineering applications.

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