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A review of non-destructive testing using robot

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Abstract. With the wide application of new materials, new structures, and new technology in modern industry especially in the aerospace industry, the range of non-destructive testing has not been limited on normal materials or normal shapes, the test of complex components will bring new chance and challenge to non-destructive testing. The combination of manipulator, robotic machine, which is widely used in industry, and non-destructive test can replace human to realize precise test on complex component, and it can get more efficiency and more security. The article reviews single manipulator gripping transducer, single manipulator gripping work piece and manipulator radiographic test respectively according to different test way, and the range of application to different test way is analyzed.

1 Introduction

With the development of robot technology, industrial robots have been widely applied in various fields such as welding, palletizing, assembly, spraying, polishing, loading and unloading. Among them, various mechanical arms designed according to different application requirements are all fall within the category of industrial robots. Robots can automatically complete specific operations according to internal procedures. They thus can replace manual labor to complete some heavy, complex and dangerous labor with high motion accuracy, high efficiency and low operating costs. Non-destructive testing technology, as a very widely used testing technology in the industrial field, is crucial for ensuring workpiece quality and reliability, and is commonly used in various fields such as aviation, aerospace, shipping, petrochemical, and so on. Non-destructive testing technology (NDT) with non-destructive advantages is increasingly focused, but industrial robots have not yet been extended to the NDT field, the combination of the two technologies is still in the research stage.

Modern part design is increasingly curved to meet the needs of hydrodynamics, space utilization, etc. The curved design not only brings new difficulties in processing and manufacturing, but also new challenges in inspection field. Curved components have been widely used in aerospace and related industries, making high-precision, efficient, and reliable inspection a key research focus in robotic non-destructive testing technology.

Non-contact NDT, ideal for complex surface inspection, offers coupling agent-free operation, high efficiency, and reliability, making it a key research focus in the field. Robotic NDT systems leverage manipulators' spatial flexibility to enable automated complex surface inspection, enhancing efficiency and safety. Typical integrations include robotic ultrasonic/eddy current testing for aircraft blade evaluation and radiation-free laser ultrasonic configurations to eliminate human exposure risks.

The robotic non-destructive testing can be divided into single-robot and multi-robot testing modes. Single-robot detection can be divided into robot clamping transducer and robot clamping workpiece, according to the different inspection objects. Among them, the robot clamping transducer is often used for inspecting large, complex curved components. During inspection, the robot moves the transducer along a preset trajectory while maintaining an appropriate distance and angle relative to the workpiece surface. This ensures accurate emission and reception of detection signals. Subsequent sophisticated signal processing and analysis then reveal internal or surface defects in the workpiece. In contrast, the robotic workpiece clamping mode is primarily employed for small, complex components. Here, the robot quickly and flexibly maneuvers the workpiece itself. This allows different parts of the component to sequentially pass through the effective area of the inspection equipment, enabling rapid inspection of multiple points or areas. At the same time, multi-robot testing can be categorized into dual manipulators holding the transducer and holding the workpiece and the transducer separately. This article reviews single robot modes.

2 Single-robot clamping transducer

In non-destructive testing, single-robot systems, including specialized robotic arms and general-purpose 6-DOF (six-degree-of-freedom) platforms, play a dominant role. Around the world, there have been a number of technological innovations to meet the needs of inspecting aerospace curved components.

Robotic NDT has evolved from single-modality inspection to multi-sensor adaptive systems, addressing growing demands for complex component evaluation. Early systems like the SQUID-based platform (ISAWA K et al. [1], Fig.1) demonstrated ferromagnetism detection in phase-transformed stainless steel but were constrained to laboratory environments. This limitation spurred the development of robotic-integrated solutions such as Ahmed et al.'s laser ultrasonic system [2], which achieved sub-surface defect detection through laser Doppler vibrometry coupled with robotic mobility-significantly enhancing signal-to-noise ratios in field applications.

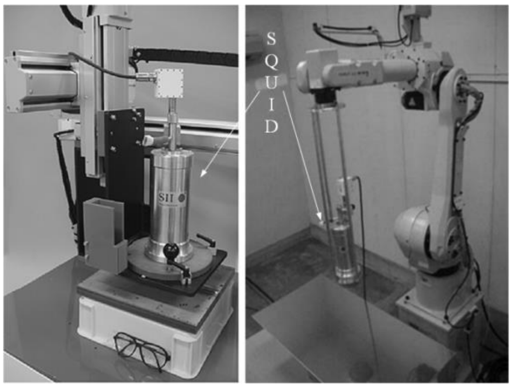

Fig. 1. SQUID Magnetic Imaging System

A critical challenge persists in defect characterization accuracy, particularly for composite materials. While Caminero et al. [3] successfully located defects using phased array ultrasonics, precise geometric determination remained problematic due to anisotropic signal scattering. Subsequent innovations focused on multi-sensor fusion and AI augmentation: Nguyen et al.'s [4] developed a steel climbing mobile robot equipped with multiple sensors. The robot can pass through narrow gaps, transition from flat to curved surfaces, and measure the depth of fatigue cracks in steel structures.

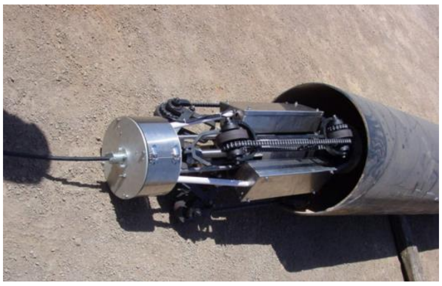

Fig. 2. Pipe Inspection Robot.
Adapted from Zhang, Y. W. (2007). Research on Coal Gas Pipeline Detection Robot System and Its Motion Control Technology. Shanghai Jiao Tong University.

Parallel advancements emerged in specialized industrial applications, exemplified by China's pipeline inspection research. Shanghai Jiao Tong University's dual-modality robot (Fig.2) [5] combined ultrasonic and eddy current sensing for internal gas pipeline defects, overcoming accessibility constraints in confined spaces. Further enhancing defect identification robustness, Ji et al. [6] developed hybrid BPNN-FOA models for welding joint assessment, whereas Chen et al. [7] achieved millimeter-level precision in surface scans through KNN-algorithm-driven robotic 3D reconstruction. The field now progresses toward closed-loop intelligent systems, as demonstrated by Yuan et al.'s deep-learning framework [8] that concurrently detects printing defects and autonomously adjusts manufacturing parameters.

In robotic NDT systems, 6-DOF robot particular efficacy for complex curved surface inspection due to their full spatial mobility within operational workspaces. These general-purpose systems enable comprehensive coverage of critical aerospace components (e.g., engine blades) and automotive parts (wheel hubs, bearings, gears) through omnidirectional positioning capabilities.

2.1 Composition of the single-robot clamping transducer

For example, the automotive wheel hub serves as a critical inspection target. As primary vehicular load-bearing elements directly impacting driving safety, hubs demand rigorous quality control encompassing both external parameters (machining accuracy, surface roughness) and internal integrity (casting defects: porosity, shrinkage cavities, residual stress). The wheel hub ultrasonic inspection system is based on robot motion control, digital signal processing analysis, numerical control technology, acoustic theory, etc. to realize the detection function. The overall composition of the inspection system is shown in Fig.3, which includes a servo controller, ultrasonic transceiver card, general-purpose 6-DOF robot, industrial control computer, inspection rotary table and water tank.

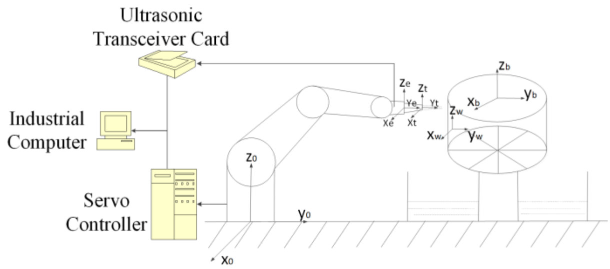

Fig. 3. Schematic Diagram of Automobile Hub Test System

The servo controller consists of PMAC (multi axis motion control card) and Yaskawa servo controller. PMAC enables simultaneous control and coordination of multiple motion axes by installing motion control cards and relevant software within the computer, leveraging the computer's computing power and the card's real-time control. Distinguished from conventional integrated servo systems, the PMAC open architecture and programmable interface enable customizable system reconfiguration, making it particularly suitable for scientific research applications requiring adaptive control development [9]. The ultrasonic detection system comprises a transducer and pulse transceiver card interfaced with an industrial computer, enabling programmable pulse transmission and signal acquisition through host computer control. The transceiver excites the transducer via piezoelectric conversion, transforming electrical signals into acoustic wave propagation through crystal vibration. A general-purpose 6-DOF robot is used as the actuator of the inspection system, which carries the transducer to realize the sweep of the wheel hub. The industrial computer coordinates the entire inspection system (Fig. 3), integrating motion control positioning data and ultrasonic waveform signals. A C++-based processing module converts localized echo signals into defect-mapped C-scan images for visualization.

2.2 Trajectory planning method for single-robot clamping the transducer

Before using the system to sweep the workpiece, it is necessary to clarify the positional relationship between the various parts of the system, and if all the components of the system are regarded as rigid bodies, the positional description of the rigid body is in the form of a combination of the position matrix and the attitude matrix. For example, a fixed coordinate system $\{A\}$ is established on the rigid body, and in the Cartesian coordinate system $\{O\}$, The position matrix is represented by the coordinate components of coordinate system $\{A\}$ concerning coordinate system $\{O\}$:

$$ {}_A^O P = \begin{bmatrix} p_x & p_y & p_z \end{bmatrix}^T \tag{1} $$

The attitude matrix is represented by the cosines of the directions of the unit vectors $\mathbf{x_A}$, $\mathbf{y_A}$, and $\mathbf{z_A}$ of the three axes of the coordinate system $\{A\}$ with respect to the three axes $\mathbf{x_O}$, $\mathbf{y_O}$ and $\mathbf{z_O}$ of the coordinate system $\{O\}$:

$$ {}_A^O R = \begin{bmatrix} cos(\mathbf{x}_A, \mathbf{x}_O) & cos(\mathbf{y}_A, \mathbf{x}_O) & cos(\mathbf{z}_A, \mathbf{x}_O) \\ cos(\mathbf{x}_A, \mathbf{y}_O) & cos(\mathbf{y}_A, \mathbf{y}_O) & cos(\mathbf{z}_A, \mathbf{y}_O) \\ cos(\mathbf{x}_A, \mathbf{z}_O) & cos(\mathbf{y}_A, \mathbf{z}_O) & cos(\mathbf{z}_A, \mathbf{z}_O) \end{bmatrix} \tag{2} $$

The positional description of a rigid body is expressed in the form of a combination of a position matrix and a pose matrix as:

$$ {}_A^O T = \begin{bmatrix} {}_A^O R & {}_A^O P \\ 0 & 1 \end{bmatrix} \tag{3} $$

For simplicity, the representation of the pose matrix is done using the X-Y-Z fixed-angle coordinate system method, where the coordinate system $\{A\}$ is first made to coincide with the coordinate $\{O\}$, then the coordinate system $\{A\}$ is then rotated by an angle r_x around $\mathbf{x_O}$, r_y around $\mathbf{y_O}$, and finally r_z around $\mathbf{z_O}$.

This simplifies the positional description of the rigid body as:

$$ {}_A^O T = \begin{bmatrix} p_x & p_y & p_z & r_x & r_y & r_z \end{bmatrix} \tag{4} $$

As shown in Figure 3, the transducer is mounted on the end-effector of the robot, and the measured workpiece is placed on the rotary table, a coordinate system $\{O\}$ is established at the base of the robot as the base coordinate system, a coordinate system $\{e\}$ is established at the end-effector to describe the end-effector position, a transducer coordinate system $\{t\}$ is established at the end of the transducer to describe the position of the transducer, a workpiece coordinate system $\{b\}$ is established at the center of the measured workpiece to describe the position of the workpiece relative to the base coordinate system $\{O\}$, and a coordinate system $\{w\}$ is established at any point of the measured workpiece.

During the sweeping process, due to the use of water jet coupling method, and thus need to transducer end and the distance between the measured point to maintain a constant. At the same time, the transducer acoustic axis coincides with the normal direction of the measured plane. That is, the coordinate system $\{w\}$ of any measured point and the transducer coordinate system $\{t\}$ always satisfy the transformation matrix ${}_t^w T$. When the measured workpiece model is known, the relationship between any point of the measured workpiece and the workpiece coordinate system $\{b\}$ can be expressed as follows. In the process of robot sweeping, firstly, the computer generates the sweeping trajectory in certain step according to the CAD model file, and then the transducer is required to run along the sweeping trajectory at a certain speed to each measured point and collect the ultrasonic signal. According to the computer-generated sweep trajectory, the transducer motion trajectory ${}_t^b T = {}_t^w T \, {}_w^b T$. Since there is a fixed positional relationship between the measured workpiece and the base coordinate system $\{O\}$, which is written as ${}_b^O T$, thus the motion trajectory of the transducer in the workpiece coordinate system $\{b\}$ can be converted to the base coordinate system $\{O\}$ by equation (5).

$$ {}_t^O T = {}_b^O T \, {}_t^b T \tag{5} $$

2.3 Example of the single-robot clamping transducer

For the automobile wheel hub, the surface structure is complex, large size, and large weight. The use of the robot clamping transducer detection method is shown in Fig.4. The ultrasonic detection method of water-jet coupling can detect casting defects such as trachoma, shrinkage cavity and shrinkage porosity in automobile hub.

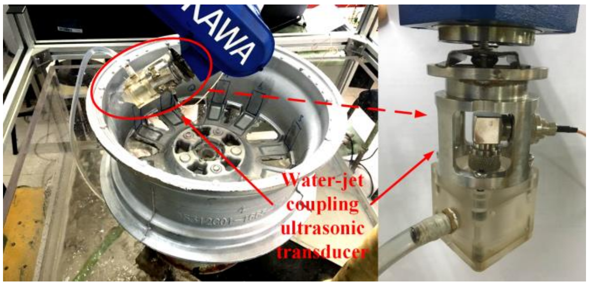

Fig. 4. Ultrasonic Test for Automobile Hub

Ultrasonic inspection is limited by resolution and can only recognize defects within the workpiece. For surface cracks caused by residual stress, fatigue or uneven casting temperatures, detection can be realized by robotic clamping of the eddy current transducer [10], as shown in Fig.5.

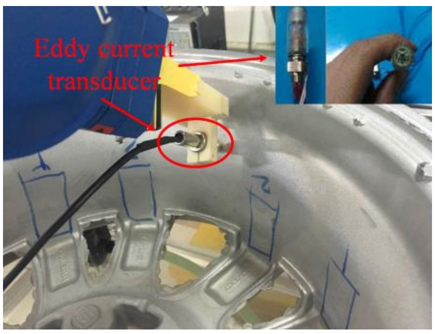

Fig. 5. Eddy Test for Automobile Hub

To detect residual stress in large curved welds, a robot-mounted ultrasonic transducer can be used. Fig. 6 shows the detection in kind of residual stress in the weld. In the Fig. 6, red areas indicate higher stress values compared to green regions, while the blue area represents an undetectable region. As seen, weld positions have higher residual stress than other areas. The heat-affected zone of the measured flat plate weld in Fig. 6 is 50 mm, and the stress concentration area aligns with the actual weld heat-affected zone size.

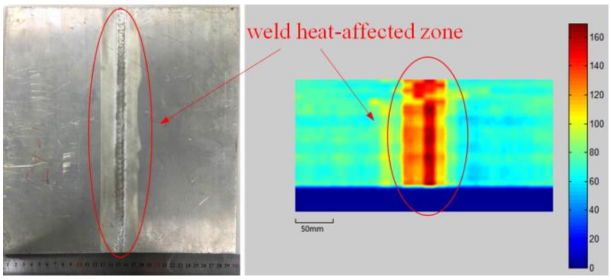

Fig. 6. Slab Welding Line Test

3 Single robot clamping workpiece

Non-destructive testing of small, complex components such as aero-engine blades, bearings, and bolts is a growing research focus worldwide. Various methods are explored globally: Hamilton et al. [11] utilized the ray - triangle intersection array algorithm for robotic arm path planning. This enabled the NDT probe to maintain a constant distance or lift height from the specimen's surface, achieving submillimeter scale and accurate surface geometries of object. Oaki et al. [12] installed BRDF imaging optical components on a robotic arm, maintaining a constant distance from the surface, to detect minute scratches on the workpiece and map defect locations to 3D CAD data. Zhao Xinyu et al. [13] utilized a line laser profilometer to acquire the point cloud data of the blade. Subsequently, they fitted the surface contour equation, planned acceleration and deceleration scanning trajectories, performed multi-axis motion decomposition, and thereby achieved automatic scanning imaging of complex surfaces. As shown in Fig.7, Tavakoli M [14] developed a 4-DOF robot for inspecting 200-350 mm diameter pipelines. These studies advance the field, offering efficient and accurate solutions for NDT challenges.

Fig. 7. Pole Testing Robots

3.1 Composition of the single-robot clamping workpiece

Smaller components are suitable for the use of the robotic clamping workpiece detection mode. Taking the aero-engine blade as the detection object, the detection system is shown in Fig.8.

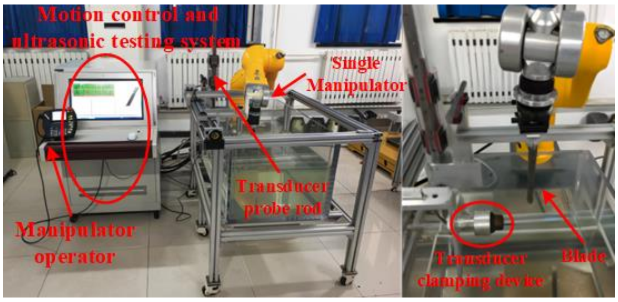

Fig. 8. Schematic Diagram of Blade Testing System

An aero-engine blade inspection system is built based on a 6-DOF robot platform. Integrating ultrasonic detection, manipulator motion control, and computer programming, it aims to automate the NDT of blade defects and thickness. The system integrates robot, ultrasonic transducer, pulse transceiver hardware, and robot motion control system and scan imaging software. It uses ultrasonic scanning to detect defects and thickness, displays real-time A-scan pulse-echo signals from the blade, extracts peak-to-peak values of A-scan defect echoes, converts them to grayscale values for C-scan color values, and presents defect and thickness data as images.

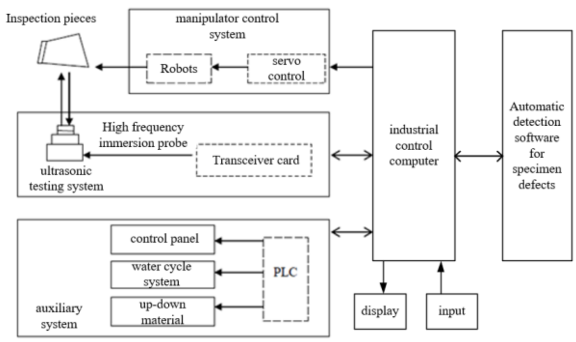

Fig. 9. Single Manipulator Test System Composition Block Diagram

Fig.9 shows the single-robot ultrasonic NDT system, which includes the manipulator control system, ultrasonic testing system, and other auxiliary modules. The manipulator control system (encompassing both hardware controllers and motion planning software) executes motion control commands for joint actuation. The whole system is coordinated by an industrial control computer. The manipulator control system uses a 6-DOF articulated robot with a repeat positioning accuracy of 0.08 mm, ensuring the positioning accuracy of the tested blade and ultrasonic transducer, and reducing the impact of errors on results. The ultrasonic testing system, with a high-speed acquisition card and pulse transceiver, can get real-time pulse-echo signals from the blade.

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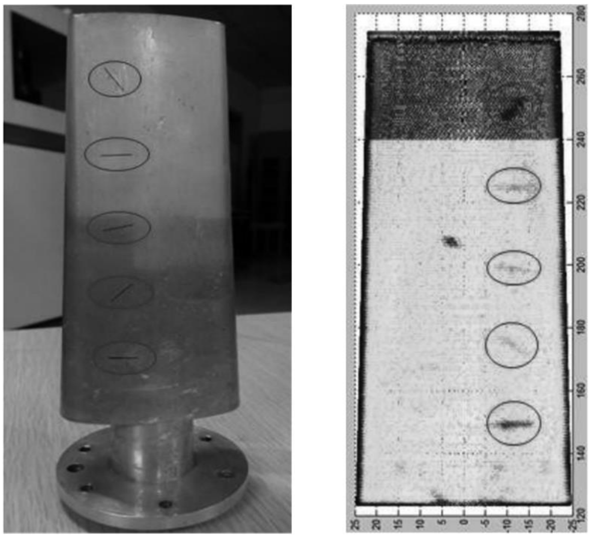
3.2 Example of the single-robot clamping workpiece

Aero-engine blades are typical complex curved components, which are suitable for the inspection method of robotic workpiece clamping due to their small size, lightweight, and high inspection accuracy requirements.

Fig. 10(a) is the imitation blade, five artificial defects of 1 cm long and 1 mm deep are made on the surface of the blade respectively, and Fig.10(b) is the corresponding C-scan inspection result, the five artificial defects can be clearly displayed in the C-scan image. And the size of the artificial defects detected by the scanner is basically the same as the actual size.



(a) Copying Blade (b) Test Result

Fig. 10. Ultrasonic Testing on Profiled Blade

The single-robot clamping workpiece detection method, known for its versatility, is applicable not only in ultrasonic testing but also in laser ultrasonic and eddy current testing. Fig.11 illustrates a single-robot holding a workpiece for laser ultrasonic detection. When the workpiece is irradiated by a laser, it absorbs the high-energy light, causing a temperature rise and expansion that generates ultrasonic waves. This method allows for contact-free, long-distance detection. Given the potential harm of lasers to humans, this approach is suitable for robotic workpiece clamping detection.

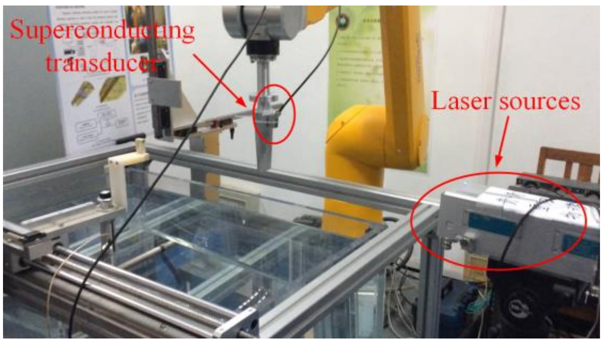


Fig. 11. Aviation Engine Blade Laser Ultrasonic Test

Fig.12 shows the eddy current inspection using a single-robot to clamp the workpiece, limited by the ultrasonic detection resolution, the ultrasonic detection method is difficult to achieve the detection of defects on the surface of the workpiece, while the eddy current test can use the detection coil to measure the changes in the magnetic field on the surface of the workpiece, which is suitable for the detection of surface defects on the workpiece [15].

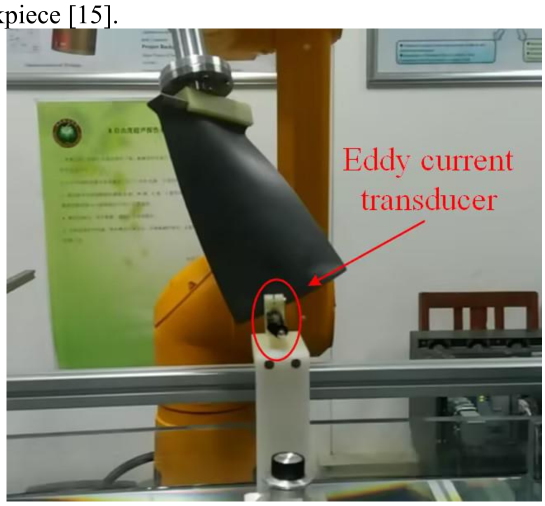


Fig. 12. Aviation Engine Blade Eddy Test

4 Conclusion

This review has comprehensively examined the integration of robotic systems with non-destructive testing methodologies for complex component inspection. The operational dichotomy of robot clamping transducer (RCT) and robot clamping workpiece (RCW) configurations addresses distinct industrial requirements: RCT demonstrates significant advantages for large-curvature components such as automotive wheel hubs and welded structures through precise transducer positioning and water-jet coupling, enabling effective detection of internal flaws and residual stresses. RCW methodologies prove particularly suitable for intricate geometries like aero-engine blades, where robotic manipulation ensures accurate positioning relative to inspection equipment.

Technological innovations in motion control systems, including PMAC-based architectures and multi-sensor integration of ultrasonic, eddy current, and laser modalities, have substantially enhanced defect detection capabilities across surface and subsurface domains. Industrial applications validate the versatility of these approaches, as evidenced by successful implementations in automotive residual stress mapping, aerospace blade inspection with clearly identifiable artificial defects, and pipeline examination within confined spaces.

Future research should prioritize the development of adaptive path planning algorithms for unmodeled geometries, collaborative multi-robot frameworks to extend operational envelopes, self-calibrating mechanisms to streamline system deployment, and energy-optimized designs for sustained field operation. The synergistic combination of robotic flexibility and non-destructive testing precision represents a transformative approach toward zero-defect manufacturing paradigms in critical sectors including aerospace composites and next-generation energy infrastructure.

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