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Robotics and Automation in NDE

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ABSTRACT

This bestowal emphasizes the use of mobile robotics for conducting inspections and Non-Destructive Testing (NDT) in various sectors, including pipeline inspection. It underscores the crucial role of regular inspections in maintaining infrastructure integrity and explains the process of creating robot prototypes for industrial applications. These robots are fully equipped to deploy NDT systems and are designed to minimize downtime or, when feasible, perform NDT in real-time to avoid costly shutdowns. Flexible automation with non-destructive imaging significantly reduces costs, minimizes dosage, integrates advanced imaging techniques, and delivers higher quality results in less time. The automated welding industry is experiencing rapid growth, driven by the technological demands of Industry 4.0, which has intensified the focus on smart sensor-equipped robotic systems. This document introduces a cutting-edge multi-robot system specifically designed for automated welding and real-time Non-Destructive Evaluation (NDE), effectively replacing outdated manual inspection methods. It clearly outlines each inspection method's advantages and challenges, showcasing the system's superior ability to detect artificially created defects. This innovative approach enables early defect detection, facilitating in-process repairs and significantly enhancing production efficiency while reducing rework rates and overall costs. Inspecting the interiors of pipes in the Oil-Gas area presents significant challenges due to their complex layout and often inadequate documentation. Accessing these pipes requires navigating a radiation shield, which complicates the inspection process and demands a more efficient solution. The current manuscript is aggressively pursuing the use of robots equipped with advanced non-destructive testing (NDE) tools to examine welds on non-ferritic steel pipes, as magnetic methods are not viable. A cutting-edge wireless robot is capable of navigating the exterior of pipes while deftly avoiding obstacles. It employs an eddy current system for swift and accurate crack detection, complemented by a real-time camera that enables immediate analysis. All data collected can be processed on-site or transmitted wirelessly for comprehensive examination, ensuring thorough inspections that meet safety standards. This thoroughly explores the robotic system, imaging acquisition, and evaluation processes to confirm the feasibility of robotic NDT and presents the system configuration.

Keywords: Non-Destructive Testing, Robots, Manufacturing Testing, Robotic Welding, Ultrasound.

INTRODUCTION

[1] Robotic Non-Destructive Testing (RNDT) seamlessly integrates robotics with non-destructive testing to enable efficient remote inspections. The four essential components of RNDT, including Monitoring, Mobility, Manipulation, and Measurement, are crucial in detecting defects in large structures, particularly in hazardous environments. Through our extensive research, we have successfully developed and implemented mobile robots that significantly reduce the cost and time required to access test sites. These advanced robotic systems effectively eliminate the need for traditional methods such as scaffolding, abseiling, and manual rope deployment by human operators.[1][2]Nondestructive testing (NDT) encompasses a range of highly multidisciplinary techniques used across various industries to assess material properties and detect defects without causing damage to the inspected components. The automation of NDT is a paramount objective for industries such as automotive, aerospace, petrochemical, power generation, and nuclear industries. Automated NDT offers significant advantages over manual inspection, including minimizing human exposure to hazardous materials and dangerous work, while significantly enhancing inspection accuracy, precision, and speed, ultimately reducing production time and labor costs. Robotic inspection provides unparalleled autonomy and flexibility, particularly in industrial scenarios involving complex geometry components or large structures. Moreover, robotic systems can be effectively deployed in remote and hazardous environments, such as nuclear waste management and radioactive areas. The Department of Energy (DOE) aims to maximize the use of robotic handling of hazardous waste to considerably enhance safety and process efficiency within its environmental restoration and waste management efforts. Remote-operated robots enable access to high radiation level areas for repairs, maintenance work, inspections, and other critical tasks.[2][3]The maintenance and

inspection of buildings, dams, bridges, and pipelines are absolutely crucial for supporting economic growth and ensuring long-term sustainability. Current visual inspection methods often fail to detect concealed damage, highlighting the pressing need for improved strategies for infrastructure inspection. Nondestructive evaluation (NDE) provides essential data for extending the life of structures, demanding a determined approach to overcome the challenges in implementing sensors for large-scale infrastructure. Various methods, such as electromagnetic and acoustic techniques, have been rigorously explored for monitoring the health of structures. Structural Health Monitoring (SHM) applications meticulously monitor parameters such as strain, load, displacement, impact, pH levels, moisture content, vibration patterns, and crack detection.

When designing a nondestructive testing (NDT) survey, a meticulous evaluation of factors such as penetration ability, level of detail required, physical property contrast, noise level, and the method's track record in construction projects is imperative.[3][4]Nondestructive testing (NDT) is crucial in manufacturing, including industries like automotive and aerospace. NDT allows for examining objects without changing their microstructure, helping to identify flaws or defects. Techniques include visual inspections, electromagnetic testing, ultrasonic testing, and more. Factors such as equipment quality, personnel understanding, and technical documentation need to be considered to optimize the testing process. NDT is increasingly important in the automotive industry, especially with composite materials. There are two main categories of NDT methods for composite materials: contact methods (ultrasonic, magnetic, eddy current, electromagnetic, and penetrant testing) and non-contact methods (transmission ultrasonic, radiographic testing, thermography, shearography, and visual inspection.[4].

MATERIALS & METHODS

[5]The methodology for real-time robotic control employs comprehensive external positional management of the robots through a correction-based Robot Control Interface (RCI) movement. This technique permits the robot controller to adjust the position of the end effector dynamically, circumventing the need to adhere to any pre-defined trajectory. During each interpolation cycle, the robot controller transmits its current position along with a timestamp as an XML string. In response, the CRIO provides an XML string that outlines essential positional adjustments for each axis. These adjustments are categorized into two types: absolute, which defines the new position in relation to the robot's base, and relative, which modifies the position concerning its current location. The adoption of relative adjustments is deliberate, as these smaller corrections enhance safety during both the development and testing phases. User-defined welding and inspection paths are entered as individual points in a table through the graphical user interface (GUI), with each column representing the Cartesian coordinates. Additional columns facilitate critical process control, such as activating welding and data logging, and selecting welding parameters from a lookup table associated with a Welding Procedure Specification (WPS).

For simpler geometrical shapes, such as plate or pipe welds, paths can be manually specified using merely the starting and ending coordinates. In contrast, more intricate geometries can be created utilizing Computer-Aided Manufacturing (CAM) or robotic path planning software and subsequently imported into the system. All pertinent process parameters and ultrasonic measurements were documented with corresponding timestamps, encoded according to the robot's positional data, and stored in a binary format for future analysis. The system was strategically designed to conduct ultrasonic inspections at three critical stages of the welding process: upon the completion of the welding procedure, during the interpass phase between consecutive welding passes, and concurrently while the arc is active, simultaneously with the weld deposition. Each assessment method presents distinct advantages and disadvantages, yet all contribute fundamentally to the prompt identification of defects. The precision and positional consistency inherent in robotic systems can be effectively utilized for post-process non-destructive testing (NDT) by performing continuous, repeated evaluations of the finished component. This capability allows for the monitoring of defects, such as cold cracking, by comparing sequential ultrasonic scans. Given the elevated temperatures generated by the welding process and any subsequent post-weld heat treatment, it is imperative to employ an ultrasonic probe assembly that can endure such high temperatures. Interpass ultrasonic NDT aids in the identification of welding defects by facilitating inspections between individual welding passes or layers.

This approach permits potential in-process repairs, as only a minimal quantity of material needs to be removed to access and rectify defects. This is particularly advantageous for the fabrication of components that are generally difficult to repair after the application of all welding passes, such as thick multipass welds and components produced through wire arc additive manufacturing (WAAM). A significant challenge in interpass welding inspection lies in the complex geometry of the sample, which evolves as the weld is constructed, thus differing from the original as-built configuration. [5][6]Following the automation of manufacturing processes, this revolution addresses the critical aspects of digital connectivity and communication among manufacturing systems, as well as quality assurance systems, including NDT and NDE methodologies. Concepts such as "smart factory" and "digital twin" are pertinent to this ongoing evolution. In addition to the automation of Computed Tomography(CT) systems for NDE 4.0, it is essential to digitize the entire NDE process. This process begins with test specifications and the corresponding guidelines and standards pertinent to the component under evaluation. The information must be transferred automatically to and interpreted by the CT system, ensuring that all handling and manipulation of the component during the inspection occurs without human intervention. Ultimately, the results of the evaluation must be reported in a digital format that is comprehensible and interpretable, enabling synchronization of the digital twin of the component with its current state. Additionally, the CT system itself may possess a digital twin, facilitating virtual planning for measurement tasks and potentially predicting expected outcomes based on various influencing scenarios related to the component. Robotic CT presents a highly suitable option for NDE 4.0.

The considerable degree of freedom associated with a robotic manipulator within a CT system allows for the execution of CT scans focused on specific areas of interest, referred to as region of interest (ROI) scans. This capability permits dynamic adaptation of the scan trajectory to accommodate the characteristics of an unknown component in real time. Rather than adhering to conventional rotational scans that require the component to circle an axis, the robot can follow more advanced trajectories, such as helical or spherical paths. The latter approach reduces the number of projections needed, as it gathers more comprehensive information when the projections are captured at uniform intervals around the component. For the digital twin associated with Robotic CT, there is no necessity for hardware beyond a standard workstation. This arrangement allows for the simulation of the states of the X-ray source, the robotic manipulator, the component being tested, and the digital detector array (DDA) through software. The control and analysis software, encompassing the graphical user interface (GUI), remains consistent between the real system and its digital twin. As a result, operators will experience no distinction in functionality when engaging with either system. Furthermore, a simulation tool can be employed to generate realistic imaging from the software, enhancing the X-ray imaging chain's simulation. For the purpose of robotic control, a general GUI can be implemented that utilizes a Cartesian coordinate system to adjust the three orthogonal translation directions and to define the pitch, roll, and yaw capabilities of the object being examined.

This interface functions independently of the manipulator currently in use, allowing users to disregard the specific details of the joint configurations associated with the underlying kinematics. Consequently, the same GUI can be utilized for traditional manipulators, effectively abstracting the manipulation unit from the ideal coordinate system. This design consideration permits even individuals without specialized knowledge in robotics to operate a Robotic CT system with ease. With the advancements introduced by NDE 4.0, the process of setting up scan trajectories without human initiation is facilitated, as test regions can be delineated solely in Cartesian coordinates, irrespective of the complexity of the underlying test system. Besides well-known defect types like pores, cracks, and inclusions, AM often leads to typical irregularities such as delamination and lack-of-fusion pores.

Lack-of-fusion pores occur when loose powder is not melted during the 3D printing process. This may happen when the power of the 3D printer's laser is locally too low for some reason, e.g., if the laser diode fails or material spatter is present in the powder bed. Generally, gas pores and inclusions are easily detected, whereas cracks and delamination are only found if they are penetrated in the same direction of their propagation. The lack-of-fusion pores are similar to flat or oval gas pores, and therefore, they also can be seen in their direction of the longer axis better than the others, but due to the fact that they are filled with loose powder, their contrast is very low and will become even lower the smaller they are. With Robotic CT, the scan trajectory can be adapted to the propagation direction easily.[6]

RESULTS

[7]Micro-defects located on complex geometrical structures present significant challenges for inspection utilizing traditional non-destructive testing (NDT) equipment, particularly in the Oil-Gas sector where components often exhibit marked thickness variations. This challenge arises from the inability to reliably track the profile of the test surface, which frequently fails to meet the high accuracy standards required for effective measurement, thereby resulting in unreliable inspection outcomes. Profile tracking is critical for evaluating the integrity and metal fatigue of complex structures characterized by large curvature. However, the precision of scanning trajectories employed in conventional NDT methods does not adhere to ultrasonic constraints due to inherent trajectory errors. Specifically, if the axis of the probe's beam is not maintained orthogonal to the test surface, the angles of ultrasonic incidence will vary, resulting in inaccurate test outcomes when standard NDT constraints are not followed. Several key challenges must be addressed for the industrial implementation of robotic NDT systems. Firstly, while specimens are generally designed to be uniform, they often display significant deviations from their corresponding Computer-Aided Design (CAD) models. This discrepancy complicates the deployment of precision NDT measurement, necessitating a flexible approach capable of accommodating manufacturing variances. The accuracy of the robotic trajectory's orientation is diminished when the robot manipulator grasps the probe or specimen, due to potential assembly errors. Traditional measuring instruments demonstrate subpar performance in underwater environments, highlighting the need for innovative methods to precisely calibrate both the orientation of the robot and the position of the probe or specimen, given the clear relationship between the work piece coordinates and the robotic tool frame. The strategy for scanning trajectories warrants careful consideration, particularly when addressing

surfaces with significant curvature. Empirical evidence suggests that ultrasonic waves with gently varying amplitudes are more effectively captured with high-speed scanning motions. Consequently, it is essential to optimize the robot's trajectory planning to enhance the efficacy of the scanning process. It is imperative to improve the positioning accuracy of the robot manipulator through effective profile tracking of the test surface, as ultrasonic non-destructive evaluation (NDE) results are significantly influenced by the robotic scanning trajectory during automated inspections. Although industrial robots possess commendable positioning accuracy, the discrepancy between planned and actual trajectories frequently exceeds the allowable limits established by ultrasonic NDT criteria. Therefore, it is advisable to calculate the robotic scanning trajectory utilizing mathematical matrix transformations. Inaccuracies or inconsistencies in the position and orientation of the robotic trajectory during automated detection may lead to mischaracterization of defects in the specimen.

The implementation of profile tracking with ultrasonic alignment is executed by an industrial robot, which serves as the core component of the ultrasonic NDT system. This system encompasses the probe, data acquisition card, and industrial control computer. Comprehensive details regarding the characteristic parameters of the hardware components are presented in a subsequent method, which offers further insights into the robotic scanning system.[7][8]The foundation of the hybrid system in the oil-gas sector provides a highly efficient energy storage capability that is both more economical and lighter than traditional batteries. Through advancements in various sector developments, the manufacturer has created a system capable of delivering high, continuously cycling power output over an extended operating life, which significantly exceeds the performance of smart chemical battery-based hybrid applications. To ensure the integrity of the filament-wound carbon composite components, alternative non-destructive verification techniques are employed, including non-destructive computed tomography (CT) scanning for every safety-critical component. The supplier intends to achieve a substantial increase in production volumes recognizing that cost reduction is imperative for the successful high-volume production of these components.

Several non-destructive testing (NDT) techniques may be applicable to thick-walled carbon composite pipes. Radiography involves penetrating the object with short-wavelength electromagnetic radiation, with the amount of radiation passing through the object captured by a detector. The degree of absorption is influenced by the material's density and thickness, while cavities and discontinuities produce detectable variations in absorption. CT scanning generates precise three-dimensional cross-sectional images of the entire component. Typical defects identifiable using this technique include delamination, undulations, porosities, fiber cracks, and impact damage. Radiographic images obtained from various perspectives are used to reconstruct three-dimensional volumes.For ultrasonic testing (UT) to be effective, the dimensions of the discontinuity or flaw must be greater than one-half of the wavelength employed. Furthermore, the quality of the results is contingent on the sensitivity and resolution of the equipment used. Sensitivity reflects the ability of a UT system to detect the smallest flaws, while resolution pertains to its capability to discern closely spaced flaws within the material and near the surface.

Both sensitivity and resolution improve as the frequency of the sound waves increases. The optimal frequency for flaw detection is also dependent on the material structure, type of flaw, size of the flaw, and its location. Higher frequencies typically result in greater vibrational scattering of energy within the material due to frequent collisions between wave particles and the material itself. This effect reduces the penetrating power of the waves, thereby limiting the maximum thickness of the material from which flaws may be detected. The intensity of the sound wave echo is also affected by the acoustic impedance mismatch between the flaw and the surrounding material; as such, an echo from a void is often stronger than that from an inclusion owing to a significant difference in impedance. The pronounced mismatch in acoustic impedance within the material facilitates the inspection of thick sections due to the generation of stronger echoes.

A broad bandwidth minimizes damping across the frequency range centered around a specified frequency, thereby enhancing the resolution of the UT system owing to a higher final frequency, albeit at the expense of penetrating power. In contrast, a narrower spectrum of highly damped frequencies may yield poorer resolution but greater penetration capabilities. Thermography testing utilizes infrared (IR) imaging to identify defects within components. An IR camera records the spatial and temporal distribution of surface temperature following the heating of the component. Defects interfere with the heat flow, thereby enabling their detection through this methodology.[8]

CONCLUSION

The field of robotic NDT is rapidly evolving, leveraging advances in electronics, robotics, sensor technology, software, and network interfaces. This depicts high-quality reports that cover key topics in robotic-enabled sensing, including in-process inspection in robotic manufacturing applications, real-time and data-driven robotic sensing, and mobile terrestrial, underwater, and aerial robotic inspection platforms. The authors present innovative solutions for enhancing the visualization and analysis of large robotically collected datasets. These advancements are essential for addressing new societal challenges within Industry 4.0. As the field continues to develop, with the integration of autonomous robotics, virtual-twin simulations, the Internet of Things, cybersecurity, cloud computing, augmented reality, and big data, this Special Issue marks the beginning of further research outcomes in the future. A cutting-edge robotic system with advanced sensors has been developed specifically for automated welding and ultrasonic inspection. This system is designed to facilitate instant communication, data collection, and real-time adjustments based on sensor data. Our ongoing research is laser-focused on eliminating false alarms caused by reflections and boosting the system's ability to identify and measure weld flaws accurately. Our future goals include enhancing the Phased Array system probe for completely dry inspections and enabling automatic defect detection, significantly reducing the time gap between flaw onset and identification for potential in-process repairs.

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