AUTOMATED NON-DESTRUCTIVE EXAMINATION OF COMPLEX SHAPES

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ABSTRACT

AREVA NDE Solutions has a long history applying robotics and advanced non-destructive examination (NDE) or testing (NDT) techniques to the nuclear industry where radiation dose and harsh environments make manual inspection undesirable. Moreover, the nuclear environment frequently demands automated inspections of critical components for long-term traceability of the inspection and to allow re-inspection results to be compared with earlier examinations. This has been particularly important for vessel and nozzle inspections from both the ID (usually underwater) and from the OD (where space permits). These technologies have been naturally extended to commercial air, rail, and steel inspection challenges using conventional automation robots. Technical challenges to adapt low-cost 6+ axis robot systems for NDE include coordinate transforms to suit the robot kinematics and the desired customer display configurations, ultrasound, eddy current and alternate NDE method triggers, scan-path planning including velocity limitations and coordinated motions plus projecting ultrasound waves from the complex surfaces into the component to be inspected with complete understanding of the UT beam path. This paper discusses extension of this technology from nuclear to industrial applications with examples of single and dual robots applying simple UT, phased-array contact UT, and zero-degree single and dual squirter systems (Figure 1).

Keywords: automated NDE, Ultrasonic Testing, High speed robot application, Composite material, Modeling

1. INTRODUCTION

AREVA NDE-Solutions historically specialized in mechanized non-destructive testing (NDT) systems for the nuclear industry. This frequently demanded development of dedicated robots...
with special hardened electronics suitable for high radiation fields. Many of the applications were for underwater components and for operations at elevated temperatures as well. Industrial robots were rarely well suited for these applications so the development teams required specialists not only skilled in using robots but also in developing complete robot solutions (Figure 2) [Ref 1]. Moreover, in the nuclear service business, only a few devices are needed since they can be shipped from site to site. The "per-robot" cost therefore was typically quite high.

In some cases however, lower cost industrial robots that are made by the hundreds and thousands could be adapted to nuclear service. This was especially true for inspection robots performing well structured tasks like surface tracking and scanning. Such adaptations enjoyed significant cost reductions from developing dedicated 6 axis robot systems but could also benefit from the robot engineering skills that were accustomed to design full robot systems since frequently, additional axes and additional degrees of freedom had to be controlled and integrated into the total package. This collection of robot engineers coupled with NDE specialists was found to also be particularly well suited to industrial robotic inspection challenges. Thus AREVA NDE solutions established a group to focus on inspection of safety-critical systems like aircraft components, steel shafts for high speed turbines, high-speed train wheels and shafts, and other components where in-service failures due to manufacturing or service induced flaws is unacceptable.

2. NDE TECHNIQUES

During the manufacturing process it is desirable to examine parts to confirm they are defect free and fit for service without destroying the part. A number of methods are available to detect any significant flaws or defects. The most common robotic techniques include various configurations of ultrasound (UT), Eddy Current and other electromagnetic techniques (ET), visual tests (VT), or visual penetrant tests (PT) (Figure 3). If one examines almost any part closely enough, blemishes or imperfections can be detected. Thus frequently the challenge is not only to detect flaws but also to size these defects supporting an evaluation to determine if the flaw is significant to the part's performance.

Pulse-echo single transducer UT is the simplest transducer set and configuration and can be applied for thickness measurements and other applications where the minimum target flaw produces a large reflection. Using the same sensor for transmit and receive however creates challenges to the electronics which tend to saturate during the time period just after the transmit pulse. This makes near-surface reflections difficult to detect and characterize.

Transmit-receive transducers involve more wires and the difficulty to mount the sensor elements co-axially complicates detection of near-surfaces for a different reason. Separating the
transmit and receive sensors however allows each separate circuit to be optimized and minimizes the chance that the transmit pulse saturating the receive electronics.

Phased array UT transducers (PAUT) add flexibility to the inspection system by allowing multiple angles and/or multiple focal depths to be created with the same transducer by simply changing the pulse focal laws within the UT instrument. Simple PA UT systems can contain 8 or fewer elements. The UT beam quality and performance however can be significantly enhanced with more elements. In some cases 2 dimensional PA systems with 128 sensors or more are used to sweep the beam in two directions. One set of focal laws is applied for each array pulse to produce a specific angle or focal depth. More modern UT instruments and software can harness the power of sampling phased array or sometimes called full-matrix-capture. This approach sequentially pulses each element in the transmit array and receives on all elements of the receive. The received signals are then mathematically adjusted to simulate a large number of focal laws.
Immersion UT systems use zero degree or angle transducers that can be flat or focused to scan the part without having the transducer touch the part surface. This can yield good sensitivity to near-surface flaws and has the added advantage of no transducer wear, low manipulator loading, and simple transducer replacement. However, the part and transducer must be underwater. For simple parts, the robots can frequently operate in-air above a water-filled tank but with complex parts, either the robot needs to be underwater, or the part must be turned to access all inspection surfaces. Immersion systems can be operated either as single-sided or 2 sided through transmission system (Figure 4).

Squirter systems offer most of the advantages of immersion systems without the burden of an immersion tank. Both the transmitted and received UT beam is transmitted through the water stream and most of the squirter water can be collected in a pan or trough below the part.

Electromagnetic test systems do not require water or gel coupling. These systems include Eddy Current (ET), Alternating Current Field Measurement (ACFM), and Flux Leakage systems that are primarily designed for near surface flaws plus Electromagnetic Acoustic Transducers (EMAT) systems that generate and detect UT waves that have passed through a part.

Visual Test (VT) and Penetrant Test (PT) systems are usually examined by the inspection personal without any robotic assistance. Indications or areas of concern can be easily photographed and documented. Occasionally, particularly on large parts, there is an interest to robotically pass a video or high-resolution still frame camera over the part to traceably document the inspection, to locate any close-up image frames of interest, and/or to allow for human-eye off-line or computer on-line detailed review of video images. Robotic interface issues include speed of camera motion, viewing angle, and associated lighting.

3. ROBOT CONFIGURATIONS

3.1 General configuration and design considerations

NDE system robots are responsible for delivering the transducers to the inspection target point plus providing position coordinates for the NDE system to associate with the NDE data. The functional system components include the robot and controller, the NDE instrument and transducer, plus a computer or computers to fuse the data (Figure 4) [Ref 3&4]. The robot may also include additional degrees of freedom to move the robot or the work-piece to allow full access to all inspection surfaces. Modern software manages all these degrees of freedom seamlessly to facilitate re-programming and re-purposing inspection lines to adapt to changing parts or requirements.

3.2 Single Robot Inspections

Single robot inspections require all sensors to access the part from only one side. This can include a simple 5 or six axis robot if all target parts of the component can be reached from a single robot base position with respect to the inspection sample. Frequently however, large components must be examined that cannot be reached from a single robot position. In these cases, additional degrees of freedom must be added to move the robot base and/or the sample to allow full access. For these types of inspections, robot positioning repeatability and relative accuracy for adjacent scan lines should be better than a few mm, but this is easily within the typical performance characteristics of most industrial robots.
3.3 Dual Robot Inspection

CFD components with concern for disbonds and layer separations, or materials whose acoustic clarity does not support UT signals passing from the inspection surface to the back-wall and then back to the inspection surface or other components where through-transmission UT is required for the inspection must use a dual robot configuration. These robots can either be setup within an immersion tank - usually with the transducers manipulated on offset tools to keep the robots above water, or using a dual squirter system. For these arrangements, the alignment between the two robots must be very accurate (from a few mm to sub-mm and angularly from a few degrees to less than one degree). The specific accuracy demand depends on the specific transducers and the inspection targets. Typically this type of accuracy demand exceeds the factory setting accuracy of the robots and their associated supplemental carriages and requires a custom calibration to optimize the Denavit - Hartenburg (Denavit–Hartenberg) kinematic coefficients for the robot and additional degrees of freedom [Ref 4]
4. THE INSPECTION PROCESS

NDE programs typically begin by establishing the sensor's ability to find flaws or defects of interest. NDE experts usually can select transducers and describe an inspection approach that will have a high likelihood of success. The chances of success can be further enhanced using computer models that consider transducer, material, geometry, and target minimum detectable flaw characteristics to produce a theoretical probability of detection or POD. This is then verified by a representative set of samples that bound the expected test configurations.

The part is then analyzed to determine the full volume and surface to be inspected. This is normally established using the CAD design. Many CAD packages including CATIA by Dassault Systems, which is most commonly used for designing aircraft parts can support this kind of analysis.

CATIA and Dassault partner software packages can also produce an optimized scan plan completely within the CAD environment. CENIT, a German Dassault partner company has produced a widely accepted scan plan generation package called FASTSURF [Ref 5]. This can interface to AREVA’s ISQUS software to complete the robot control and NDE acquisition process [Ref 4]. Thus, the entire scan setup can be performed off-line. The FASTSURF package accommodates scanning around holes, fasteners, and irregular edges to achieve full coverage without allowing the sensors to fall off an edge or be damaged by scanning across a discontinuity. Moreover the complete motion feasibility including self-collision and part discontinuity collision can be anticipated without experimental evidence and avoided beforehand. This minimizes down-time for the machine and provides a completely traceable engineering justification package for the inspection. Moreover, the inspection system can be completely re-configured and tested in software before interrupting the line to adjust or completely re-purpose the inspection cell.

Alternatively, the scan plan can be established completely within the robot native programming environment by manually teaching the scan pattern (Figure 7).

In years past, the NDE systems could only deal with 2-D position information and even today this is frequently the display mode of choice.
More advanced software however can now adapt to irregular surfaces to adjust the surface position and / or the scan angle to assure target volume is inspected. This data can also be used to display the data in 3-D corrected coordinates for a more accurate representation of the location of ultrasonic reflections. (Figure 8)[Ref 6].

5. CONCLUSIONS

Robot systems developed primarily for manufacturing applications can be and are being cost-effectively adapted to NDE inspections of complex surfaces. This is particularly true for safety critical industries like nuclear, high-speed rail, and aircraft/aerospace. Frequently, these manufacturing robots must be coupled with integrated gantry systems to adjust the position of the robot or the sample to allow full inspection access of the target surface. The complexity, inspection speed, positioning accuracy, and display choices depend on the application. These robot systems are particularly suited for complex shape inspection.

6. ACKNOWLEDGMENTS

Examples discussed above are taken from the AREVA NDE Solutions portfolio. For additional details, interested parties are encouraged to contact the authors.

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