Robotic Non-Destructive Inspection

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Abstract

Automation of non-destructive testing (NDT) of engineering components and structures represents one of the strategic objectives of many industries. It enables increases in accuracy, precision and speed of inspection while reducing production time and associated labour costs in contrast to manual inspection. The use of robots can provide additional flexibility and autonomy to automated NDT. Automated robotic inspection can be beneficial in diverse industrial scenarios ranging from integration of NDT into the manufacturing process of components with very complex geometry, such as gears, to periodical in-service overhaul of large structures (for instance, in petrochemical and aerospace industries). In this work we present an application of a six degree of freedom robotic positioner (KUKA KR5 Arc HW) for automated NDT by means of multiple inspection techniques. We investigate the potentials for automated toolpath generation and future potential for improving path trajectory through real time measurement of tool position.

1. Introduction

Non-destructive testing (NDT) encompasses a wide range of techniques aimed at evaluation of material properties and detection of defects, both surface and internal. Principal users of NDT include the automotive, aerospace, petrochemical and power generation industries. Inspection of numerous components (for instance, in automotive manufacturing) or extended structures (for instance, aircraft skin) is laborious and time consuming. Some NDT techniques, such as video inspection, eddy currents testing (ECT) and ultrasonic testing (UT) can be readily automated and there has recently been a growing interest in the development of robotic systems for NDT \(^{(1)}\). There are numerous applications of climbing robots \(^{(2)}\) and autonomous miniature robotic vehicles for use in NDT \(^{(3)}\) these being suited to inspection of large structures where access by human operators may be hazardous or limited. In this paper we shall focus on the application of conventional industrial six axis robotic positioners which are more suited to inspection of smaller components, particularly associated with inspection at the manufacturing stage. Previous work has included a six Degrees of Freedom (DOF) robotic arm (Mitsubishi MELFA RV-1A) , used for robotic scanning of various test
pieces by means of eddy current (EC) technique\(^4, 5\). A seven-axis robotic arm transportable by climbing and walking robots (CLAWAR) was developed to deploy NDT probes to perform inspection of very large and critical infrastructure located in hazardous environments\(^6\). The EloScan system using a six DOF heavy-duty industrial robot KUKA KR 15/2 has been designed for the eddy-current inspection of rotationally symmetrical components of aircraft engines\(^7\). Due to its universal design the system is claimed to be able to scan complex geometries that require precise probe guidance and a high repeating accuracy.

Complex shape surfaces, as opposed flat planes or other symmetrical geometries, poses a number of challenges from the point of view of scanning path programming. When discrete points on the inspection path are recorded manually (so called “teaching”), the process can be very laborious, and requires that the location can accessed by the operator. There is a possibility to use automated tool-path generation which is widely used in aeronautical, automotive and other manufacturing industry\(^8\). CAD/CAM software such as Delcam and Robotmaster eliminate the need to use the “teach” method to program a robot and considerably shortens the toolpath generation process\(^9\).

A significant problem in the field of production line automation is the design of flexible and autonomous robotic systems able to manipulate complex objects\(^10\). Most current systems depend on complete knowledge of both the shape and position of the parts. When CAD data for the part are not available, there is a need for efficient manipulators that can recognize complex and unorganized objects with little or no prior knowledge about the pose and geometry of the parts\(^11\). The technique described in\(^12\) can be used to construct a geometric model of an unknown environment, based on data acquired by a laser range finder on board a mobile robot. Details of the steps to be followed to describe the environment, including range image acquisition and processing, 3D surface reconstruction and the problem of merging multiple images in order to obtain a complete 3D model are presented in the report.

In CAD systems, a surface to be machined is expressed by a series of curves, such as B-spline, Bezier and non-uniform rational B-spline (NURBS) curves, which compose the surface and in CAM systems the curves are divided into a large number of line or arc segments. These divided movement commands can cause many problems including the excessive size of NC data which makes local adjustment or modification of the surface almost impossible. To cope with those problems, the necessity of real-time curve or surface interpolators can be helpful\(^13\).

An additional problem arises in the fact that real parts often deviate from their respective CAD models. Adaptive manufacturing describes the ability to introduce inspection into the machining process and make real-time decisions to improve that process\(^14\). Adaptive manufacturing consists of two related technologies, adaptive fixturing and adaptive machining. In adaptive fixturing, inspection data is collected and used to align the toolpath to the real-world part. The CNC toolpath is standard and does not change part to part. In adaptive machining, the NC program changes to match the real-world part\(^14\).
Our ultimate goal is to integrate the described features of surface reconstruction and automated tool-path generation into robotic NDT scanning of test pieces with complex shapes. In this paper we present the results of our initial study of robotic NDT scanning of metallic and composite test pieces by means of ultrasonic technique. The obtained results for more challenging composite material are compared with results obtained by means of conventional C-scanning using a scanning acoustic microscope (SAM).

2. Experimental Setup and Samples

Figure 1 explains the experimental setup. A robotic arm KUKA 5 arc HW with KCP 2 controller (15) was used to deploy a Panametrics ultrasonic immersion transducer V309 (16), as shown in Figure 2. The principal specifications of the robotic arm are given in Table 1. The principal specifications of the ultrasonic immersion transducer are given in Table 2.

![Figure 1: Setup diagram.](image1)

![Figure 2: Photograph of KUKA Robotic Arm](image2)

<table>
<thead>
<tr>
<th>Table 1. KUKA 5 arc HW principal specifications.</th>
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<tr>
<td><strong>Maximum reach</strong></td>
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<tr>
<td><strong>Rated payload</strong></td>
</tr>
<tr>
<td><strong>Max. total load</strong></td>
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<tr>
<td><strong>Positional repeatability</strong></td>
</tr>
<tr>
<td><strong>Number of axis</strong></td>
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<tr>
<td><strong>Precision</strong></td>
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<tr>
<td><strong>Number of Digital Inputs &amp; Outputs</strong></td>
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A pulser-receiver (Parametrics 5052PR) was utilised to drive the ultrasonic transducer. A digital oscilloscope Tektronix DPO4054 was used for the UT waveforms acquisition.
Its main characteristics include 500 MHz analogue bandwidth and sampling rates up to 2.5 GS/s.

**Table 2. Principal specifications of ultrasonic immersion transducer.**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
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<tbody>
<tr>
<td>Frequency</td>
<td>5.0 MHz</td>
</tr>
<tr>
<td>Nominal Element Size</td>
<td>0.5” (12.7 mm)</td>
</tr>
<tr>
<td>Focal distance</td>
<td>2” (51 mm)</td>
</tr>
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A digital input/output device Agilent U2121A was used to interface control signals between the robot controller and the control PC.

Initial experiments comprised the scanning of a simple steel test block of dimensions: 100 mm x 70 mm x 12 mm. This test-piece featured four through holes drilled near the corners and a hole of 50% depth at the centre of the slab, as shown in Figure 3. The four holes in the corners had a diameter of 10 mm, whereas the centre hole had a diameter of 7 mm. The steel slab was placed in a water-filled tank with the central hole facing downwards, thus representing a sub-surface defect.

![Figure 3. Steel test-piece.](image)

![Figure 4. CFRP plate.](image)

There is currently a need in the aerospace industry to develop a method of efficient inspection of composites materials. Therefore we also scanned a carbon-fibre-reinforced polymer (CFRP) plate (Figure 7). It had a thickness of 4mm and featured a circular depression in the centre caused by impact damage. The system performed a raster scan of a rectangular area (18mm x 25mm) around the defect and the signals were recorded at intervals of 0.25mm in both x and y direction.

In order to validate the results obtained by robotic UT scanning, the raster scan of the CFRP sample was carried out with an industrial Scanning Acoustic Microscope PVA TePla SAM 300 (17), using the same transducer as before. The device was able to record the signals at intervals of 0.1 mm in both x and y direction but, because of the used ultrasound transducer (5 MHz), the maximum theoretical resolution is equal to 0.3 µm.
3. Results and Discussion

A post-processing MATLAB script was developed to evaluate the amplitude and/or the time-of-flight (TOF) of the acquired UT waveforms. We evaluate the maximum, minimum and peak-to-peak (P2P) amplitude in a given time window of interest, or register the differences in the TOF for the first echo of the longitudinal wave. The TOF is measured in relation to the peak of the signal Hilbert transform, in order to make the measurement insensible to the wave phase. Figures 5 and 6 show the more representative results of the C-scan.

![Figure 5. UT response: P2P signal.](image)

![Figure 6. UT response: ToF](image)

The results clearly demonstrate that the central hole is subsurface and allows to accurately evaluate its diameter. Moreover, smaller surface imperfections (corrosion) can be observed. The average speed of the system, evaluated as number of scanned points per minute, was equal to 88 points/min.

Figure 7 shows the most significant images obtained on the CFRP plate. The circular depression in the centre is clearly recognizable in both the peak-to-peak value and maximum of the Hilbert transform section images. Looking at both images, the red region near the centre demonstrates that a higher energy was reflected back at the focussed layer, corresponding to the position of the actual structural damage.

![Figure 7. Robotic C-scan images of CRFP plate with a circular depression: Peak-to-peak amplitude value (left) and maximum of Hilbert transform (right).](image)
Figure 8 shows results obtained by SAM on the CRFP plate with a circular depression: The original image was produced by the system (left) and the rainbow-scale image was obtained with MATLAB (right). Owing to the higher speed of acquisition, SAM can enable smaller scan steps and thus better spatial resolution. It is our objective to achieve similar speeds of inspection and spatial resolution using a robotic arm for larger and more complex objects.

![Figure 8. SAM images of CRFP plate with a circular depression: Original image produced by the system (left) and Rainbow-scale image (right).](image)

4. Conclusions

We have presented preliminary findings in using an industrial 6 axis robot positioner to perform C scanning of two test coupons (one steel, the other CFRP). Using a PC to interface and control both ultrasonic data acquisition, and an industrial robot controller, we have demonstrated the feasibility of ultrasonically scanning simple geometry components. Simple point by point scanning, and more sophisticated linear motion with positional data measurement from the robot controller have been implemented. For purposes of comparison, the CFRP sample was scanned with a conventional acoustic microscope, and the results compared favourably with the six axis robot ultrasound scan.

The future goal for our approach is to inspect more complex geometry components, where the true flexibility of the six axis approach will be demonstrated. In particular methods of generating automatic NDT scanning toolpaths from CAD models will be investigated and compared with manual approaches. Emphasis will be placed on independent metrology verification of these toolpaths to quantify the performance of the system when operated on complex geometry components.

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References