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PAUT inspection of complex-shaped composite materials through six DOFs robotic manipulators

C Mineo, S G Pierce, B Wright, I Cooper and P I Nicholson

The requirement to increase inspection speeds for the non-destructive testing (NDT) of composite aerospace parts is common to many manufacturers. The prevalence of complex curved surfaces in the industry provides significant motivation for the use of six-axis robots for the deployment of NDT probes in these inspections.

The IntACom project, developed by TWI Technology Centre (Wales) and supported by a number of major aerospace partners and the Welsh government, has produced a prototype robotic NDT system. The prototype system is capable of inspecting complex-geometry composite components with great time savings. Two six-axis robotic arms deploy end-effectors carrying phased array ultrasonic testing (PAUT) probes. A simple-to-use graphical user interface (GUI) has been developed to control all aspects of the robotic inspection, from initial loading of part data, through scanning of the part to data analysis. The collaboration between TWI and the University of Strathclyde has boosted the establishment of new approaches for robotic tool-path generation, targeted to NDT inspections. Many unique features, such as the real-time B-scan for optimisation of PAUT settings and the external control of the robotic manipulators to allow returning to points of interest, increase the usefulness of the inspection process. This paper presents an overview of the project and of the research outcomes.

Keywords: IntACom, NDT, composite, robotic, path-planning.

1. Introduction

The growing deployment of composite materials through a range of industries is well known. In the aerospace industry, the uptake of composites has been driven by the desire to improve stiffness-to-weight ratios and develop lighter structures, and to improve corrosion, impact and fatigue resistance. Big steps have been made in these areas, but the cost of manufacture of composite structures is still a concern. This is partially caused by the cost of raw materials, but mainly due to the labour-intensive manufacturing techniques. The aerospace regulatory requirements to inspect every aerospace part can result in the NDT process being the cause of a slowdown in production. The possibilities offered by modern technologies enable the development of ever more complex component geometries. This then necessitates the deployment of more advanced and faster NDT inspections in a production environment. Some applications of six-axis robotic arms in the NDT field have been published during the last few years and there is a growing interest in using such automation solutions amongst many manufacturers within the aerospace sector.

The aim of the IntACom development project was to reduce the time taken for the inspection of complex-geometry composite components by a factor of four. This reduced inspection time has been achieved by addressing three areas: automation of inspection, employment of advanced PAUT and software enhancement through the use of techniques such as assisted defect recognition and scan display management.

The project has produced a robotic NDT inspection prototype system capable of inspecting complex geometries in an improved manner compared to the traditional UT immersion tanks. The heart of the system is an inspection cell comprising two six-axis robotic arms, capable of working independently and cooperatively. The robotic arms deploy end-effectors carrying ultrasonic transducers, which are mounted into water jet nozzles that provide suitable water columns to guide the ultrasonic beams from the probes to the surfaces of the samples. The developed software enables data acquisition for effective robotic PAUT. A single, seamless operator interface controls all aspects, from the initial loading of CAD part data, through scanning of the part to data analysis. Several path-planning approaches have been investigated for suitable generation of robotic NDT inspection tool-paths.

This paper presents an overview of the main project outcomes and a vision for future research and development.

2. The IntACom project – platform for effective robotic NDT

TWI has established a robotic cell at its facilities in South Wales (Port Talbot). The cell was defined to be able to inspect all areas of a 3 × 1 × 1 m volume. Despite the limited workspace of the cell, the robotic inspection prototype system is fully scalable and replicable in production environments. The safety enclosure of the cell surrounds a 5 × 5 m space, with two robots that are able to stream positional data at a high speed and work either independently or cooperatively. Figure 1 shows the final developed IntACom robot cell.

The robots integrated into the robot cell are two KUKA KR16 L6-2 robot arms. These were selected for their maximum reach, with a 1600 mm reach for each arm. They are each equipped with a six-axis force/torque sensor that is used for tool trajectory error compensation. The robots are connected to a central computer running the software that provides the control for both robots.

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Carmelo Mineo and Stephen Gareth Pierce are with the University of Strathclyde, Department of Electronic & Electrical Engineering, Glasgow G1 1XW, UK. Email: carmelo.mineo@strath.ac.uk

Ben Wright, Ian Cooper and Pascual Ian Nicholson are with TWI Technology Centre (Wales), Port Talbot SA13 1SB, UK.
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accuracy and payload capability. There is further payload capability on the shoulder of the robot. The main features are given in Table 1.

Table 1. KUKA KR16 L6-2 principal specifications[6]

<table>
<thead>
<tr>
<th>Feature</th>
<th>KR16 L6-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Payload</td>
<td>6 kg</td>
</tr>
<tr>
<td>Maximum total load</td>
<td>36 kg</td>
</tr>
<tr>
<td>Maximum reach</td>
<td>1911 mm</td>
</tr>
<tr>
<td>Maximum speed</td>
<td>2 m/s</td>
</tr>
<tr>
<td>Number of axes</td>
<td>6</td>
</tr>
<tr>
<td>Position repeatability</td>
<td>&lt;±0.05 mm</td>
</tr>
<tr>
<td>Controller</td>
<td>KR C4</td>
</tr>
<tr>
<td>Protection classification</td>
<td>IP 65</td>
</tr>
</tbody>
</table>

The cell has been equipped with a water circulation system, comprising two independent pumps (one for each robot) and a large stainless steel water collection tray placed on the floor, between the plinths of the two robots. Each pump can deliver up to 20 l/min water flow to a water jet nozzle mounted on the end-effector of the robot, through a 1 inch-diameter flexible hose capable of following the motion of the robot joints during complex movements. A 1.5 m-wide and 2.5 m-long jig table is mounted on the draining tray to facilitate accurate positioning of the samples of interest and fast calibration with good repeatability.

The nozzles used project a narrow jet of water, coupling the ultrasound generated by the embedded probe onto the surface of the part being inspected. 3D printing has been used extensively to enable rapid prototyping of multiple versions of water jet nozzles. Figure 2 shows two of the water jet nozzle 3D-printed prototypes, designed to support flat and concave ultrasonic phased array probes. These nozzles provide laminar water columns and allow suitable ultrasound coupling with high curvature surfaces. The water circulation system is set to deliver 8 l/min water flow to each robot when the nozzle in Figure 2(a) is used. The necessary water flow is reduced to 1 l/min for the nozzle in Figure 2(b) because of its smaller aperture.

Although it is intended that other inspection methods can be deployed on the robotic manipulator system, the main objective is a system able to carry out inspections using PAUT. The reason for using phased array ultrasonic transducers rather than single-element probes is to take advantage of the wide area coverage available and to increase the scanning speed. Both pulse-echo and through-transmission inspections have been implemented. Two Peak NDT Micropulse 5PA systems were selected[7]. They provide 128/128 active channels individually or 256/256 channels when connected together.

3. Data acquisition software

The robot manipulators and the Micropulse 5PA systems have a strong potential to provide a great deal of flexibility for fast and effective NDT inspections of large curved samples. However, the Micropulse systems come with only very rudimentary focal law calculation and imaging software and a fully-functioning phased array imaging and analysis system was needed. Moreover, the new software developed under the IntACom project has the fundamental function of integrating the two systems, through encoding the ultrasound data coming from the Micropulse with the positional information coming from the robot controller. One of the main objectives of the IntACom project was to develop a fully-integrated data acquisition software solution, allowing NDT experts to easily collect data through the robotic system and analyse it with new types of data imaging for curved surfaces and complex geometries.

Figure 3(a) shows the fundamental structure of the IntACom software. It has been carefully designed to enable fully-integrated communication with the robots and phased array controllers. The main application, developed in the C# programming language, controls the GUI and behaves as a server application. The C++ language was chosen to write the acquisition module. Unlike C#, C++ is suitable for developing real-time data acquisition algorithms.

Figure 3. Software structure (a) and software graphic user interface with a newly-imported sample model (b)
that run in a reliable manner. The programmer can avoid the periodic, automated creation and disruption of allocated memory, which is known as garbage collection\[8,9]\.

The main application receives data from the acquisition module through a local TCP/IP connection. The acquisition module connects to the robot controller through a one-way or two-way UDP/IP Ethernet connection and to the Micropulse with a TCP/IP connection.

Figure 3(b) shows the GUI during the definition of a new part. The software can import standard tessellation language (STL) CAD files\[8\]. The STL format was chosen because it is supported by the majority of existing software packages; it is widely used for rapid prototyping and computer-aided manufacturing. The format only describes the surface geometry of a three-dimensional object without any representation of colour, texture or other common CAD model attributes. The STL file format can specify a CAD part in either ASCII or binary. Support for the binary representation was chosen because of its smaller data size. The software analyses the nodes of the STL mesh while importing the CAD model; all the disjointed surfaces of the sample are automatically recognised through counting the number of triangles that share each of the nodes in the mesh.

Every sample has multiple surfaces and each one of them requires specific inspection settings. Therefore, the operator is able to select the surfaces of interest, name them with tags and associate the desired ultrasonic testing (UT) settings. The complete definition of the UT settings involves the specification of a well-organised list of options, ordered in six groups (Figure 4): probe management, probe settings, inspection settings, sweep settings, focal settings and controller settings. The probe management group allows the definition of linear or curved phased array (PA) probes with the specification of the number of active elements and pitch.

The probe settings group gives a graphic representation of the probe elements and their Cartesian coordinates, relative to the centre of the array. The inspection settings group allows parameters such as the water path and the speed of sound to be set. The sweep settings, focal settings and controller settings are used to define the focal laws.

An ASCII-based communication protocol over Ethernet is used to command the Micropulse. The software automatically generates the ASCII command script to be sent to the Micropulse. This is a set of instructions for the phased array controller to generate the necessary focal laws, fire the PA probe with the defined voltage and pulse repetition rate and acquire A-scans according to the correct time window, sampling rate and gain.

The operator does not need to use extra portable screen-equipped PA instruments to check if the inspection set-up is correct. The IntACom software can send the command script to the Micropulse and trigger the start of the data acquisition. This allows the operator to obtain a preview of the probe profile, the real-time B-scan and the A-scans. This is very useful for optimising the position of the probe above the sample surface. Figure 5 shows a screenshot of the preview data, obtained after setting the parameters to the values given in Figure 4.

The activation of the data acquisition module, to get preview information through the UT instrument, also provides the possibility to obtain statistics about the acquisition performance. The acquisition speed, in terms of the number of B-scans per second or frames per second (FPS), depends on several parameters: the number of elements in the probe, the sub-aperture width, the step (in a linear sweep), the length of the water path (tool offset) and the length of the A-scans (related to the thickness of the specimen). The theoretical FPS is calculated considering only physics, computing the time it takes for the ultrasound to travel to the backwall surface of the specimen and come back to the probe and multiplying it by the number of A-scans in the B-scan. The real FPS is obtained by monitoring the actual quantity of data the UT instrument is able to stream to the acquisition software. The real FPS is always smaller than the theoretical FPS because of the delays caused by the necessary commands that the software needs to send to the Micropulse in order to trigger the acquisition of each B-scan, and the time taken by the Micropulse to process and return the UT data. The statistics include the maximum robot speed; it is calculated according to the FPS and the desired scanning increment (the resolution in the passive direction of the probe), defined in the inspection settings.

The statistics given in Figure 5 show a typical inspection using a 64-element phased array transducer. The tool offset, the probe coverage and the probe speed are important input parameters for the generation of the robot tool-path, and are described in the following section.

4. Path-planning approaches

The simplest programming method for industrial robots is to use a teach pendant to program in a matrix of points and to interpolate between these points using predefined movement types. However, using this method for the inspection of a complex geometry is very time consuming. Specifying the area on the
component geometry to be inspected and determining the associated scan paths is better achieved through offline programming (OLP) in order to reduce the set-up time. The goal is to be able to load the inspected component geometry CAD file into a software application, to allow the operator to pick the areas to be inspected and for the software to then generate the scan path for the robots. OLP was achieved within the IntACom project using commercial robotic simulation and programming software\cite{11}. The chosen software was CENIT-FastSurf\cite{12}, based on a Delmia platform\cite{13}.

FastSurf provides the ability to ‘build’ a robot cell, complete with components and manipulators, in a three-dimensional virtual environment. Many simulation models of the robots currently in use are available and each model contains kinematics data. Added functionality in the simulation and OLP software allows for 3D CAD data from the component to be imported, resulting in the automatic generation of scan paths on identified surfaces on the 3D CAD representation of the component. Figure 6 shows the TWI robot cell as it is mapped out in the FastSurf virtual environment and two moments during the simulation of the tool-path for the inspection of the main skin of a carbon fibre composite material aerospace winglet.

Figure 7 provides a schematic representation of the overall inspection process. Once the robot motion has been simulated and the scan paths optimised through the OLP, the resulting robot language script is generated for transfer to the robot controller.

The probe is manipulated by the robot arm according to the predefined tool-path. At the same time, the robot motion data is collected by the acquisition module. Once the data is collected, it is sent to the GUI for post-processing and analysis.

It is usual for NDT operators to double check some suspect areas of a part after an initial inspection. For such situations, generating specific tool-paths for all the areas of interest through commercial path-planning software would be time consuming and not very practical. A MATLAB-based path-planning module has been purposely developed to be integrated into the IntACom software. The path-planning software add-on is able to use the original tool centre point (TCP) data, received from the robot during the initial scan, in order to generate a specific tool-path for returning to the point of interest and executing what is called a ‘sub-scan’. The original robot trajectory is interpolated to generate the desired type of sub-scan tool-path: raster, segment or single point. Figure 8 shows the simulation of a raster sub-scan before execution.

Figure 6. TWI robot cell as it is mapped out in the FastSurf virtual environment (a); tool-path simulation (b)

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Figure 7. Schematic representation of the robotic inspection procedure
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The execution of the sub-scan is carried out through controlling the robot arm via the UDP/IP Ethernet connection established by the acquisition module. The UDP/IP connection to the robot is one-way during the initial inspection and two-way when returning to a point is required. Changing the connection from one-way to two-way has a significant effect on the acquisition module control loop. Adding in a new direction of communication adds an additional layer of network communication and data packet processing logic. Figure 9 shows the process flow diagram for one-way and two-way robot communication.

Figure 8. Screenshot of the integrated path-planning module during the simulation of the sub-scan tool-path

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Figure 9. Process flow diagram for one-way (a) and two-way (b) robot communication
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The process loop has been expanded to incorporate a new element, receiving communications from the server (ie the main application). Based on the communication received, the application must either update the demand position or exit the loop. In the first instance, a new demand position is registered, but the robot cannot travel to this point instantaneously. First, a robot packet must be received to indicate that the robot is beginning its next interpolation cycle. Next, a new coordinate must be formulated, which the robot
can reach within one interpolation cycle (ie 4 milliseconds). This may be less than the coordinate requested by the server, hence the need for a ‘demand’ position and a ‘current’ position. The next ‘current’ position is sent to the robot and the original process loop can then proceed. In the second instance, an ‘end’ command is received. However, the loop cannot simply exit since the approaching and retracting motions are carefully pre-calculated to avoid collision between the robot and the part/surroundings. An intermediary step is therefore required to navigate the robot back to the origin so that a safe retraction can begin. This is achieved by setting a new demand position, coincident to the origin (0,0,0,0,0), and waiting until the ‘current’ position matches the ‘demand’.

5. Results

A scan image of a curved reinforced wing skin was scanned using the prototype system. Its main-skin surface has a surface area of 1.6 m². It was scanned using ultrasound pulse-echo phased array inspection, using the setting parameters given in Figure 4.

Figure 10 shows the time-of-flight (TOF) C-scan of the large curved surface obtained with the IntACom prototype inspection system. The resolution is uniform across the C-scan and equal to 0.6 mm. The stand-off between the water jet nozzle and the sample was set to 8 mm. The skin thickness varies across the sample and the stiffeners are clearly seen. The sample contains some tape insert defects, as indicated by the black ovals in Figures 10 and 11. The smallest defect has been sized at 5 mm wide and the biggest at 15 mm.

Figure 10. C-scan of the main skin surface of the aerospace composite winglet

Figure 11 shows a close-up of the first group of defects. The GUI of the IntACom software lets the user analyse the collected data through visualisation of the B-scans and A-scans. The B-scan is given on the right-hand side of the screen; the A-scan section is at the bottom. The B-scan is very useful to size the C-scan features and the potential defects.

Figure 11. Close-up of one of the defect regions

6. Conclusions and future work

The IntACom project aimed to develop a robot-based system for the rapid automated inspection of complex-geometry composite components with the objective of increasing inspection throughput by a factor of four. The result is a demonstrator system that is capable of inspecting complex geometries, and with a high throughput. The results presented in this paper were acquired with a 0.6 mm resolution in the passive and active axes, and a velocity of 76 mm/s. Scans at more typical resolutions of 1.2 mm and a scan width of 29 mm achieve scanning speeds of 200 mm/s. This far exceeds the ‘4× faster’ inspection requirement when comparing to other current methods.

Depending on the number of elements in the phased array and the maximum robot arm velocity selected, the capability of the IntACom system far exceeds the capability of current gantry-based immersion tank systems. In addition, the system uses fully integrated software that intuitively steers the user through the inspection process. A simple-to-use graphical user interface (GUI) has been developed to control all aspects of the robotic inspection, from initial loading of part data, through scanning of the part to data analysis. Many unique features, including the real-time B-scan for optimisation of the PAUT settings and external control of the robotic manipulators to allow returning to points of interest, increase the usefulness of the inspection process.

Future work is related to the development of real-time dynamic UT adaptation for probes scanning highly-curved surfaces, support for UT through-transmission inspection of samples with variable thickness and implementation of metrology for part position assessment and surface mapping.

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