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DEVELOPMENT OF A FAST INSPECTION SYSTEM FOR COMPLEX COMPOSITE STRUCTURE - THE INTACOM PROJECT

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Abstract

The increasing use of composite materials across a range of industries is well documented. This has been driven by a desire to improve stiffness to weight ratios, to improve corrosion, impact and fatigue resistance and to reduce the cost of manufacture. Although great strides have been made in these areas the cost of manufacture is still a concern. This is partly due to the high cost of raw materials, but also due to the historically labour intensive method of manufacture.

IntACom is a three year development project with the aim of reducing the time taken for inspection of complex geometry composite components by a factor of four. The heart of the system will be an inspection cell comprising two 6-axis robotic arms each capable of working independently and cooperatively. The arms will deploy end effectors carrying ultrasonic transducers coupled to state of the art Phased Array Ultrasonic Testing (PAUT) or full matrix capture (FMC) acquisition systems. A simple to use graphical user interface (GUI) will control all aspects from initial loading of part data, through scanning of the part to data analysis. This paper gives an overview of the progress to date.

Key words: IntACom, NDT, composite, robotic, inspection, ultrasound.

1.0 Introduction

IntACOM is a three year development project with the aim of reducing the time taken for inspection of complex geometry composite components by a factor of four. It will do this by addressing three areas: (1) Automation of current manual inspection; (2) Enhancement of existing semi-automated systems through the use of multiple transducers and Ultrasonic phased array technology (PAUT); (3) Software enhancement through the use of techniques such as assisted defect recognition and scan display management.

The heart of the system will be an inspection cell comprising two 6-axis robotic arms each capable of working independently and cooperatively. The arms will deploy a variety of end effectors such as ultrasonic transducers coupled to state of the art Phased Array Ultrasonic Testing (PAUT) or full matrix capture (FMC) acquisition systems. A single operator interface will control all aspects from initial loading of part data, through scanning of the part to data analysis.

2.0 Robotic Manipulator

The ability to inspect complex geometry components is vital for the project partners and 6-axis robotic arms offer greater dexterity than multi axis gantry systems. A key requirement was that the Cartesian positional data could be streamed fast enough to allow rapid scanning speeds whilst accurately encoding transducer position. A robot cell containing two KUKA KR16 units has been installed at TWI's Port Talbot facility. Figure 1 shows the cell. Still to be constructed is the water collection tray and water supply for the water jets. Each robotic arm is capable of independent and cooperative movement allowing scanning of two components or two areas of a single component simultaneously, or through transmission scanning.

Figure 1: The IntACom Robot Inspection cell showing a large component under test

2.1 Probe holder with collision protection

In order to protect the system and test components from unwanted collisions crash protection has been implemented in the robot end-effector. Microswitches trip as the magnetic holder begins to separate triggering a stop command to the robot controller. The custom designed magnetic holder has adjustable retention to cope with a variety of inspection tools. Figure 2 shows the developed magnetic holder, supporting the most recent prototype of coupling water jet nozzle.

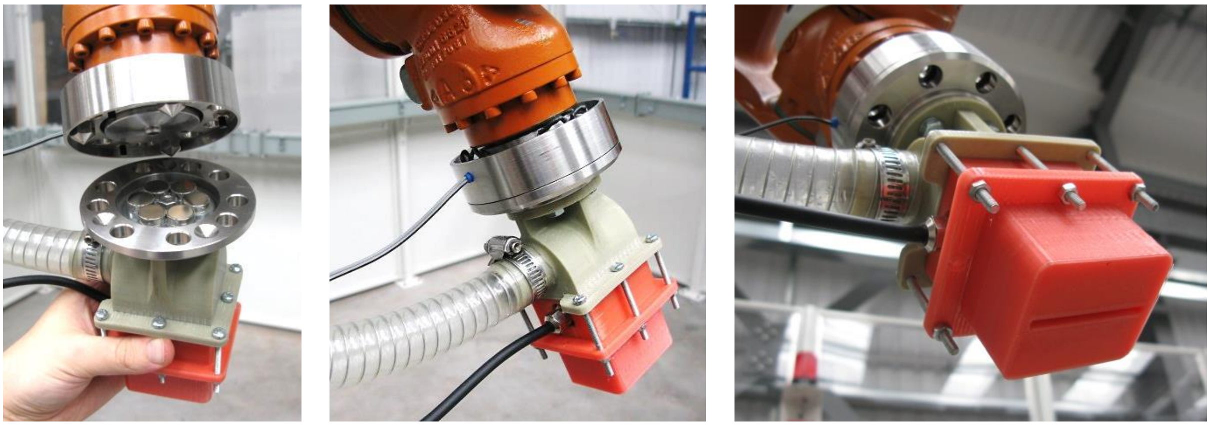


Figure 2 – Magnetic holder and water jet nozzle prototype mounted to the KUKA KR16 L-6 robot extremity.

2.2 Path Planning

Although it is possible to use a teach pendant to program in the required scan paths, using this method for inspection of a complex geometry is very time consuming. It is much quicker and less prone to errors using off-line programming (OLP). Ideally the operator would load the inspected component geometry CAD file into a software application, which would allow him to pick the areas to be inspected after which the software would then generate the scan paths for the robots. OLP can be achieved either by using commercial robotic simulation and programming software or by writing path planning software from scratch.

Commercial software provides the ability to ‘build’ a robot cell, complete with components and manipulators. Added functionality in the simulation and OLP software allows for 3D CAD data from the component to be imported, resulting in automatic generation of scan paths on identified surfaces on the 3D CAD representation of the component, as shown in Figure 3. Once the robot motion has been simulated and the scan paths optimised through the OLP, the resulting robot language script is generated and sent to the robot controllers. Trials of several commercial path planning software packages has taken place at MTC, TWI Wales and Strathclyde University. The

Fastsurf package from Cenit has been procured as it enables all the scanning scenarios detailed in the requirements specification.

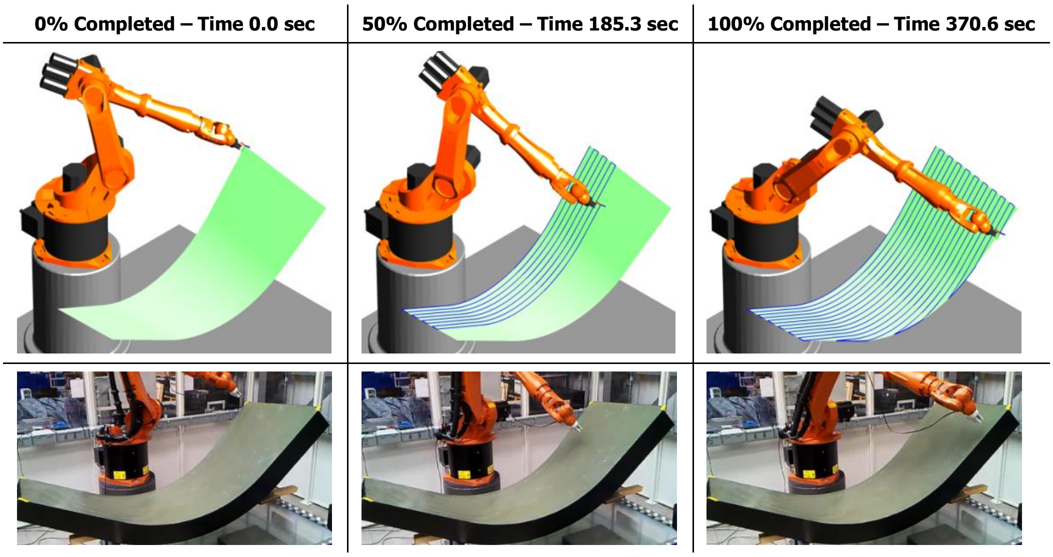


Figure 3: Cell with part positioned and paths mapped out in the MATLAB environment

3.0 Software

A software application is under development to provide a single platform for inspection setup, data acquisition and results visualisation. The functionality provided at present includes the import and registration of CAD data to represent the scanned component, ultrasound parameter selection and visualisation, and data acquisition.

3.1 CAD import

The CAD importer loads geometric data from an STL format CAD file. A manually entered offset value is used to migrate the CAD data to match the coordinate system of the developed scan paths, so that scan data can be related to the component geometry. Once loaded, the data is split into discreet surfaces by grouping those faces which share nodes, requiring that a small separation be introduced between faces on different surfaces. The grouping is achieved through an algorithm which works in two phases;

Phase 1

- Create an indexed list of unique coordinates, each with references to the faces of which they are a member.
- Create an indexed list of faces, replacing the node coordinates in each face with a reference into the node list.

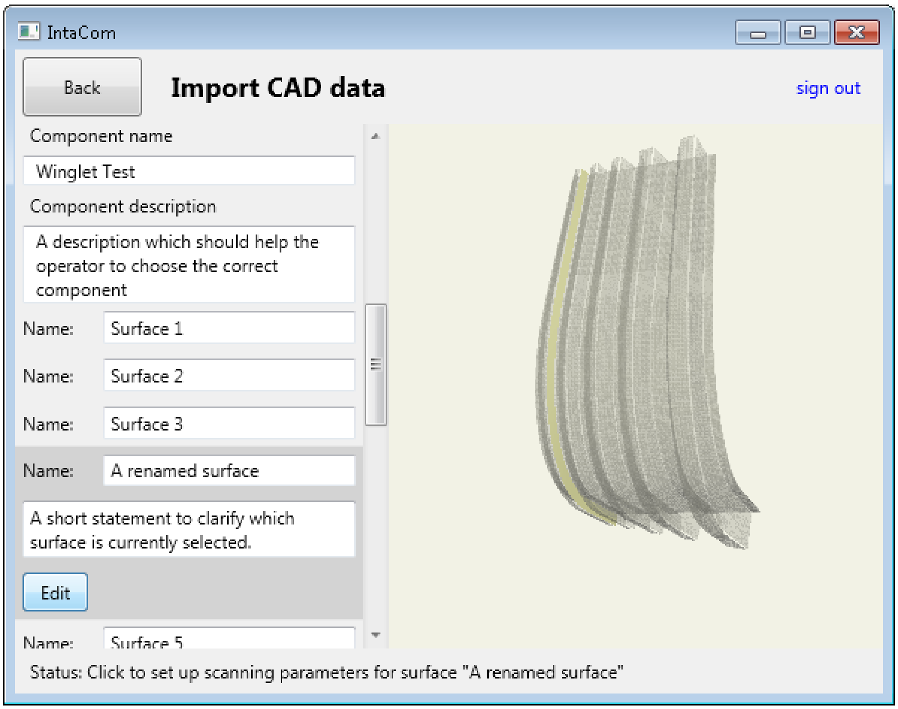
The performance of this phase is improved by discretising the volume of the CAD file and compiling a small list of nodes for each sub-volume. This greatly reduces the amount of searching required to identify recurring coordinate values, and gives an identical output if the resulting lists are merged.

Phase 2

- Create face groups by recursive use of the two lists

Each surface is created by first selecting a single face, the node references of which allow each coordinate to be quickly found from the node list. Each node also contains a reference to the other faces to which it is attached, which can be retrieved easily from the face list. Skipping between the two lists in this manner allows the algorithm to exhaust quickly and efficiently the supply of connected faces. The next surface is created by selecting the next available face and the process repeats until every face in the data set has been assigned to a surface.

The isolated surfaces can be used to differentiate between scanning areas in the subsequent setup process, as shown in Figure 4.



Import CAD data

Component name: Winglet Test

Component description: A description which should help the operator to choose the correct component

Name: Surface 1

Name: Surface 2

Name: Surface 3

Name: A renamed surface

A short statement to clarify which surface is currently selected.

Name: Surface 5

Status: Click to set up scanning parameters for surface "A renamed surface"

Figure 4: CAD import screen

3.2 Ultrasonic Array Control

Although it is intended to deploy other inspection methods on the robotic system, the majority of inspections will be carried out using phased array ultrasonic testing (PAUT). This will give wide area coverage with each scan pass thereby increasing effective scanning rates without the need for high speed movement of the transducers. A custom software suite has been developed to allow for fully functional and customizable phased array inspections using Micropulse 5PA array controllers. The application can accept probes with any pitch and up to 256 elements (with two Micropulse units operating in Master-Slave mode) and is configurable to account for different wedge or water path angles and depths.

Parameterized control of the array controller is provided, giving access to voltage, pulse-width, receiver gain, sample frequency, pulse repetition frequency, on-board frequency filtering and gating settings. Beam steering and focusing have been implemented, with focusing distance defined through depth, offset or range. Dynamic Depth Focusing (DDF) has also been included, to allow for more challenging focusing conditions as show in Figure 5. Each inspection point can trigger a single acquisition or multiple acquisitions, using linear electronic sweeping or sectorial scanning (as pictured below) to provide spatial coverage without any extra mechanical movement of the probe. Figure 6 shows the setup screen for the array control software. Visualization of the array controller command script and a representative illustration of the expected beam path help to minimise the risk of incorrectly entered setup parameters.

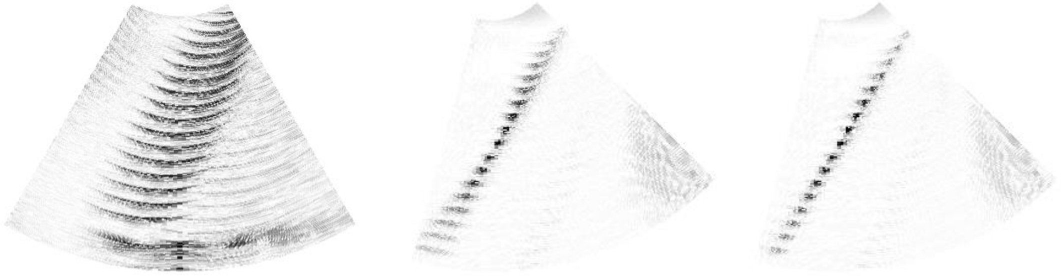
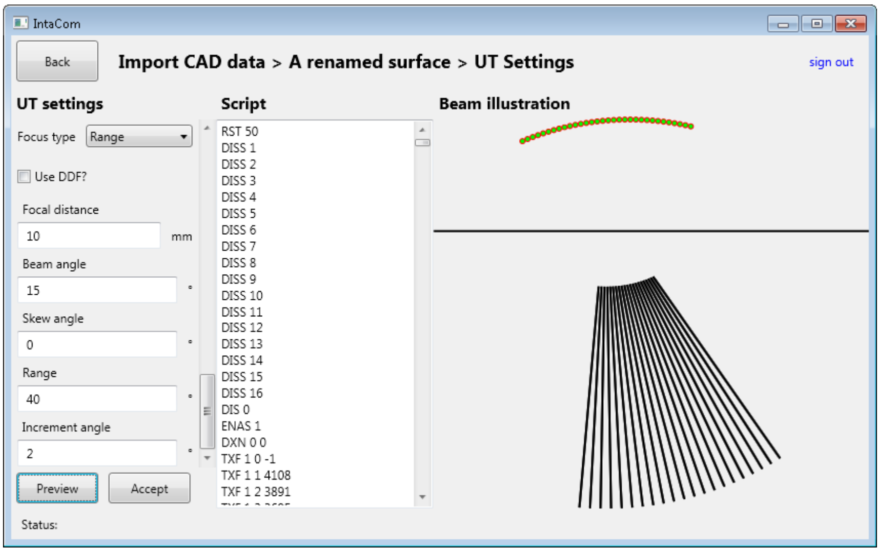


Figure 3: Sector scans unfocussed (left), focused mid-thickness (middle) and with DDF (right).



Focus type: Range

☐ Use DDF?

Focal distance: 10 mm

Beam angle: 15 °

Skew angle: 0 °

Range: 40 °

Increment angle: 2 °

Status:

```
RST 50
DISS 1
DISS 2
DISS 3
DISS 4
DISS 5
DISS 6
DISS 7
DISS 8
DISS 9
DISS 10
DISS 11
DISS 12
DISS 13
DISS 14
DISS 15
DISS 16
DIS 0
ENAS 1
DXN 0 0
TXF 1 0 -1
TXF 1 1 4108
TXF 1 2 3891
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Figure 6: Ultrasound setup screen

3.3 *Data acquisition*

Data acquisition is achieved by manipulation of two separate sources of data; coordinate feedback from the robotic elements and inspection data from the ultrasonic array controller. The coordination of these two sources, and particularly the need to continually prompt the ultrasound equipment for acquisitions, necessitates a stable processing platform, as any delays will result in gaps in the acquired data. Figure 7 shows the data processing route identified as the most efficient. The considerations affecting the design are that using C# over C++ for user interface development is considerably more efficient, while using C++ over C# for data acquisition is considerably more stable. In order to make the best of both languages, a number of points of isolation were introduced between the display and the original data processing;

1. C# buffer – prevents the transfer of data between C++ and C# being disrupted by delays in the file handling or display code
2. C++ → C# TCP connection – prevents automated C# memory management functions from disturbing the C++ processing loop
3. C++ buffer – minimises the affect of delays in the C# “receive” code on the C++ “process” code

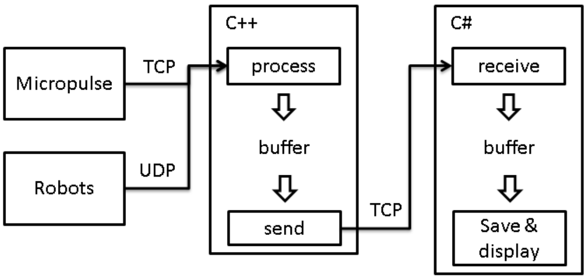


Figure 7: Data flow diagram

Figure 8 shows some example results from the acquisition system, using dummy ultrasound data (data acquired from the ultrasonic array controller without a probe attached, to create the same processing overhead). The inspection captured a set of 32 results (1 every 1mm perpendicular to the scanning direction) for every 1mm scanning increment, moving at 100mm/s, while updating the 3D coordinate history overlay in real time.

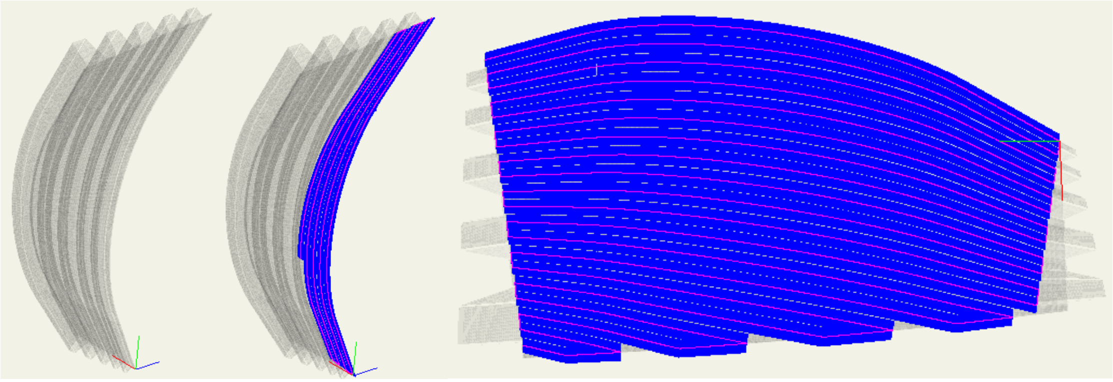
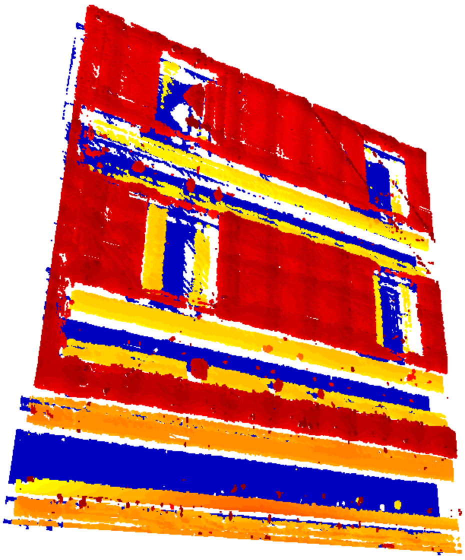


Figure 8: Example scan progression, showing CAD data with robot tool-point history (pink) and surface scan coverage (blue) superimposed



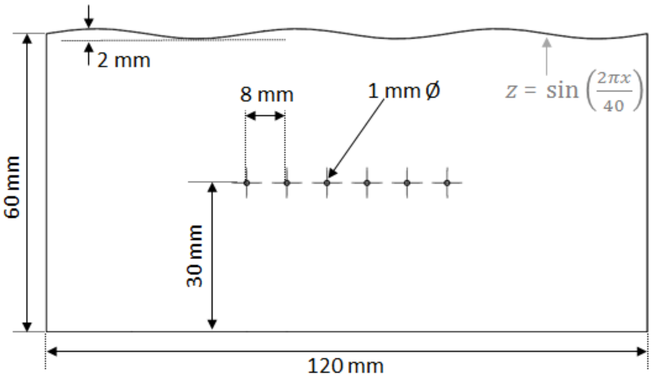


Figure 9: Example 3D visualization

Figure 10: Sample used for testing surface compensation

A flat carbon composite panel with stringers and ribs on the back face was scanned. A linear electronic sweep was used to acquire a 30mm wide swathe of A-scans, reducing the number of passes required to scan the component. Figure 9 shows a 3D visualisation similar to a C-Scan Time-Of-Flight plot that was subsequently constructed.

3.4 Interface Detection

One of the disadvantages of using large linear arrays on curved components is that some parts of the array will not be normal to the surface, resulting in refraction of the sound at unpredicted angles into the composite. This will cause difficulty when sizing and locating indications and can cause artefacts in the image. If the interface can be detected during scanning, adjustments can be made to the focusing algorithms to account for the refraction. Triangulation was used to estimate the location of the couplant-sample interface, with each array element firing individually and the echo response being received at the transmitting element and its neighbour.

Figure 10 shows a test block used in the testing of this method. Figure 11 gives some example results, using the Total Focusing Method to create a fully focused image using data acquired in Full Matrix Capture mode. Three thresholding methods of increasing complexity were used to detect the first significant echo in the echo response data. The Simple Threshold Method uses a fixed value threshold, the Threshold Crossing Method uses a fixed value threshold but normalizes each data set, and the Cross Correlation Method correlates the echo data with an idealized input signal to isolate genuine reflections [1-3]. All three methods give a marked improvement over the assumption of a linear surface profile, showing the four side-drilled holes in the right positions. Further work is required to allow the surface profile information to be used to adapt a phased array inspection. A linear electronic scan is envisioned where the origin and beam angle of each inspection point can be adjusted to suit the orientation of the surface at the target location.

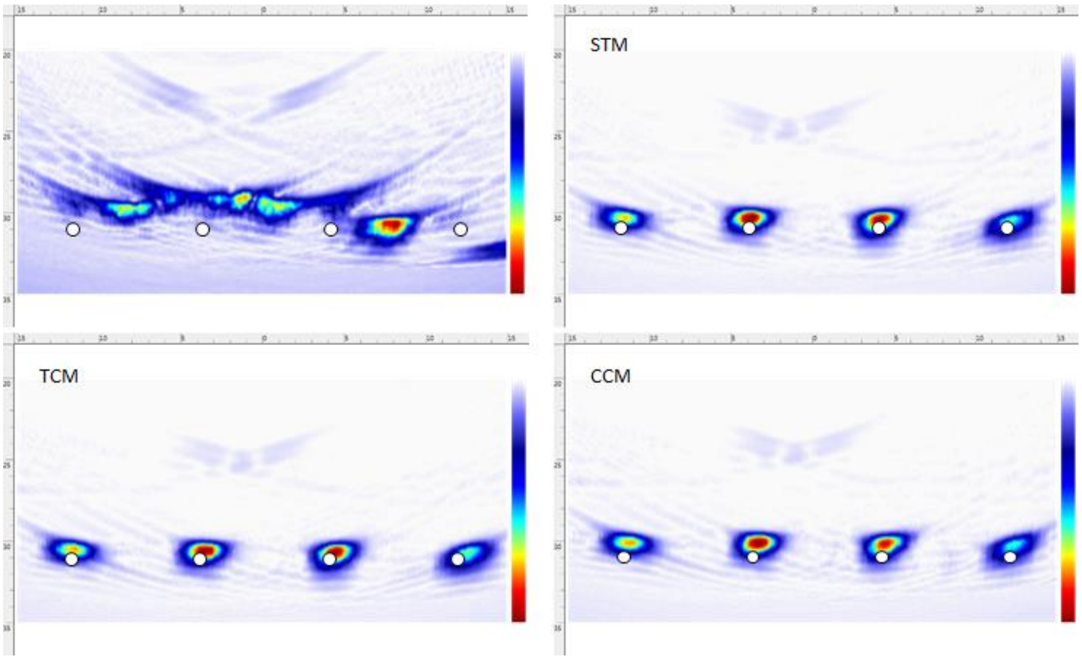


Figure 11: Focused imagery using the Total Focusing Method (TFM) and interface data from the Simple Threshold Method (STM), the Threshold Crossing Method (TCM), the Cross Correlation Method (CCM) or assuming a linear profile.

4.0 Modelling Of Fan Blade

One of the parts submitted to the project for inspection is a composite fan blade. Through transmission inspection is very challenging due to the highly curved shape and the anisotropic acoustic properties. Ultrasonic velocity can vary significantly at non-zero degree angles within the material leading to inaccurate inspection results. This effect can be minimized by using an incidence beam normal to the inspected surface when scanning a part with parallel surfaces. However, as the fan blade is a twisted aerofoil, the beam path becomes complicated. It is not sufficient simply to place the transducers opposite each other as refraction at the emergent interface will be at non-zero degree angles that will vary with position.

A simulation using CIVA 10 was carried out to simulate the beam paths through the part. The blade was divided into a number of sections as shown in Figure12. It can be seen that cross section varies with position. A robot will position the transmitter normal to the inspection surface and a second robot will be used to manipulate the reception probe to a position determined by the simulation. This process is illustrated in for a cross section 220mm from the blade root in Figure13. The exit position of the beam from the blade for each transmission probe position will be input to the 2nd robot arm. Initial simulation was based on the assumption of isotropic acoustic properties as ply layup details were not available. The results show that the beam bending effect is small. The results will be tested experimentally to see if the isotropic simulation can be used.

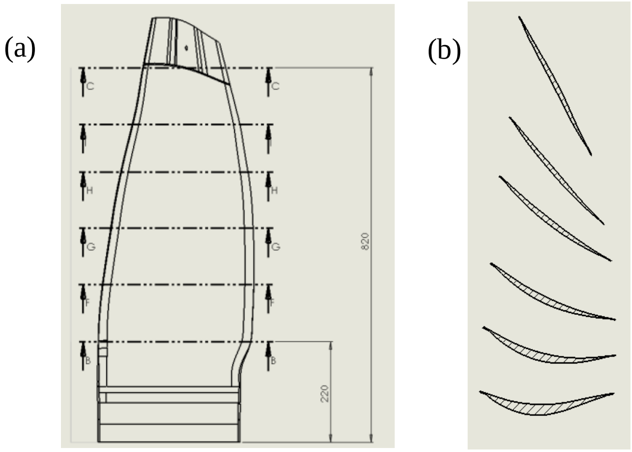


Figure 12: CAD drawings of the composite fan blade: (a) the blade divided into a number of sections; (b) the cross section views of different sections.

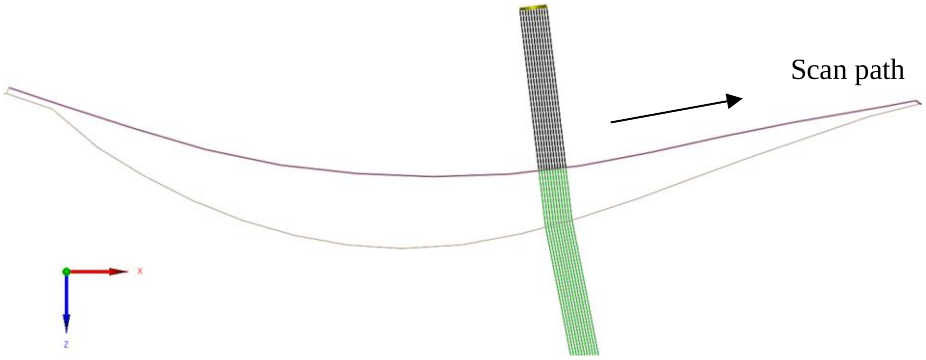


Figure 13: Through transmission beam simulation at a cross section 220mm from the blade root.

5.0 Summary

The IntA*COM* project aims to develop a robotic system for the rapid automated inspection of complex geometry composite components with the objective of increasing inspection throughput by a factor of four. A robotic system comprising two KUKA KR16 6-axis arms has been installed and a number of commercial and in-house off-line path planning tools have been trialled.

In-house designed software has been designed to import CAD files, extract inspection surfaces and map acquired data to the CAD image. A fully featured PAUT software control module has been developed for integration with the other components of the inspection system. An interface detection and mapping system has been developed allowing the use of wide arrays with irregular curved surfaces.

Modelling has been undertaken to develop the optimum scan paths when inspecting highly curved non-parallel surfaces such as those found in fan blades.

The project is being developed by TWI Technology Centre (Wales) at Port Talbot and is scheduled for completion in June 2014.

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