PAUT inspection of complex shaped composite materials through 6 DOFs robotic manipulators

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Abstract

The requirement to increase inspection speeds for 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 6 axis robots for 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 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 6-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. 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, like the real time B-scan for optimization 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 will give an overview of the project and of the research outcomes.

Key words: 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, 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 production slowdown. The possibilities given by modern technologies enable the development of evermore complex component geometries. This then necessitates the deployment of more advanced and fast NDT inspection in a production environment.

The aim of IntACom development project was to reduce the time taken for 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 geometry in an improved manner compared to the traditional UT immersion tanks. The heart of the system is an inspection cell comprising two 6-axis robotic arms, capable of working independently and cooperatively. The robotic arms deploy end-effectors carrying ultrasonic transducers, 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 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 in its facilities in South Wales (Port Talbot). The cell was defined to be able to inspect all areas of a 3x1x1m 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 5m x 5m space with two robots that are able to stream positional data at high speed and work independently or cooperatively. Figure 1 shows the final developed IntACom robot cell.

Figure 1. IntACom robot cell.

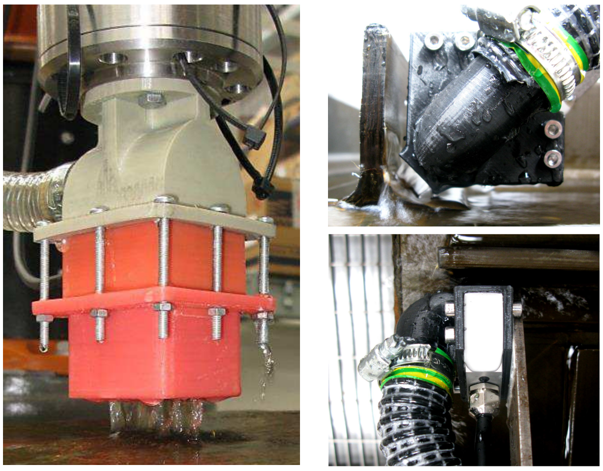
The robots integrated into the robot cell are two KUKA KR16 L6-2 robot arms [(1)]. These were selected for their maximum reach, accuracy and payload capability. There is further payload capability on the shoulder of the robot. The main features are given in Table 1.

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

	KR16 L6-2
Payload	6 kg
Maximum total load	36 kg
Max. reach	1911 mm
Max. speed	2 m/s
Number of axes	6
Position repeatability	<±0.05 mm
Controller	KR C4
Protection classification	IP 65

The cell has been equipped with a water circulation system, comprising two independent pumps (one for each robot) and a large water collection stainless steel tray placed on the floor, between the plinths of the two robots. Each pump can deliver up to 20 litre/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 1.5m wide and 2.5 m long jig table is mounted on the draining tray and allows accurate positioning of the samples of interest and fast calibration with good repeatability.

3D printing has been used extensively to enable rapid prototyping of multiple versions of water jet nozzles. Figure 2 shows some of the water jet nozzle 3D-printed prototypes, designed to support flat and concave ultrasonic phased array probes and generate suitable coupling with high curvature surfaces, through laminar water columns able to support the ultrasonic beams.



(a) (b)

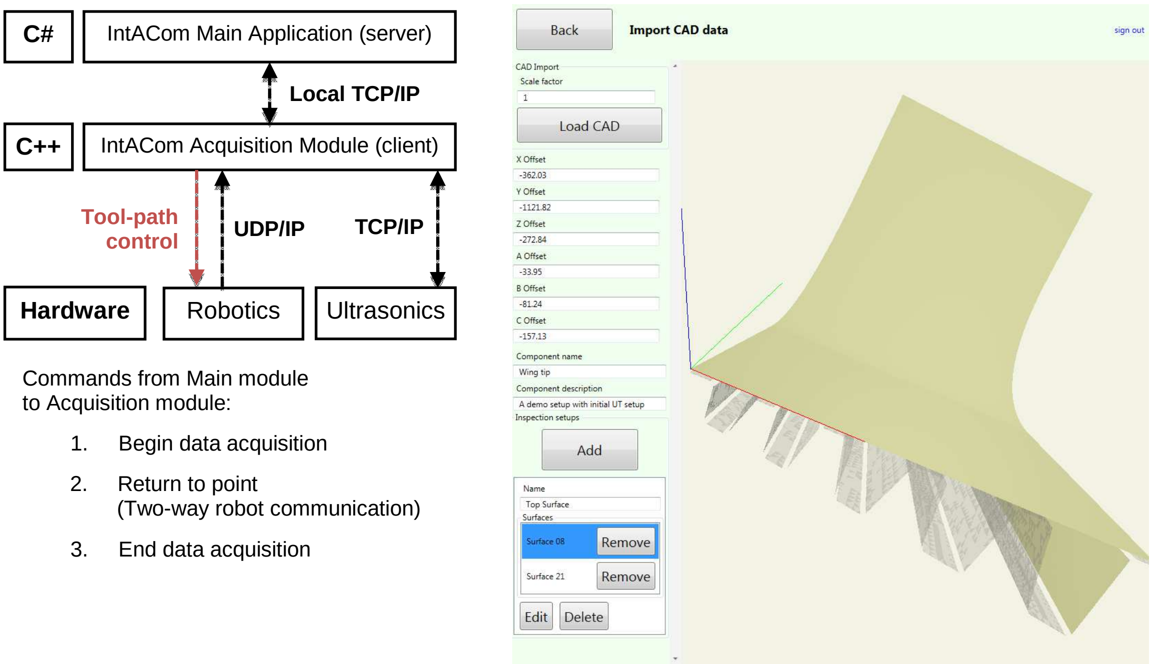
Figure 2. Two of the water jet nozzle prototypes, designed to support flat (a) and concave (b) ultrasonic phased array probes.

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 to use phased array ultrasonic transducers rather than single element probes is to take advantage of the wide area coverage available and increase the scanning speed. Both pulse-echo and through-transmission inspections have been implemented. Two Peak-NDT Micropulse 5PA systems were selected [2]. 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 have a strong potential to give 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 imagining for curved surfaces and complex geometries.

Figure 3a 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 to develop real-time data acquisition algorithms 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 [3, 4].



(a) (b)

Figure 3. Software structure (a) and software graphic user interface with a newly imported sample model (b).

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 3b shows the GUI during the definition of a new part. The software can import Standard Tessellation Language (STL) CAD files [(5)]. The STL format was chosen because it is supported by the majority of the 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-organized 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 number of active elements and pitch.

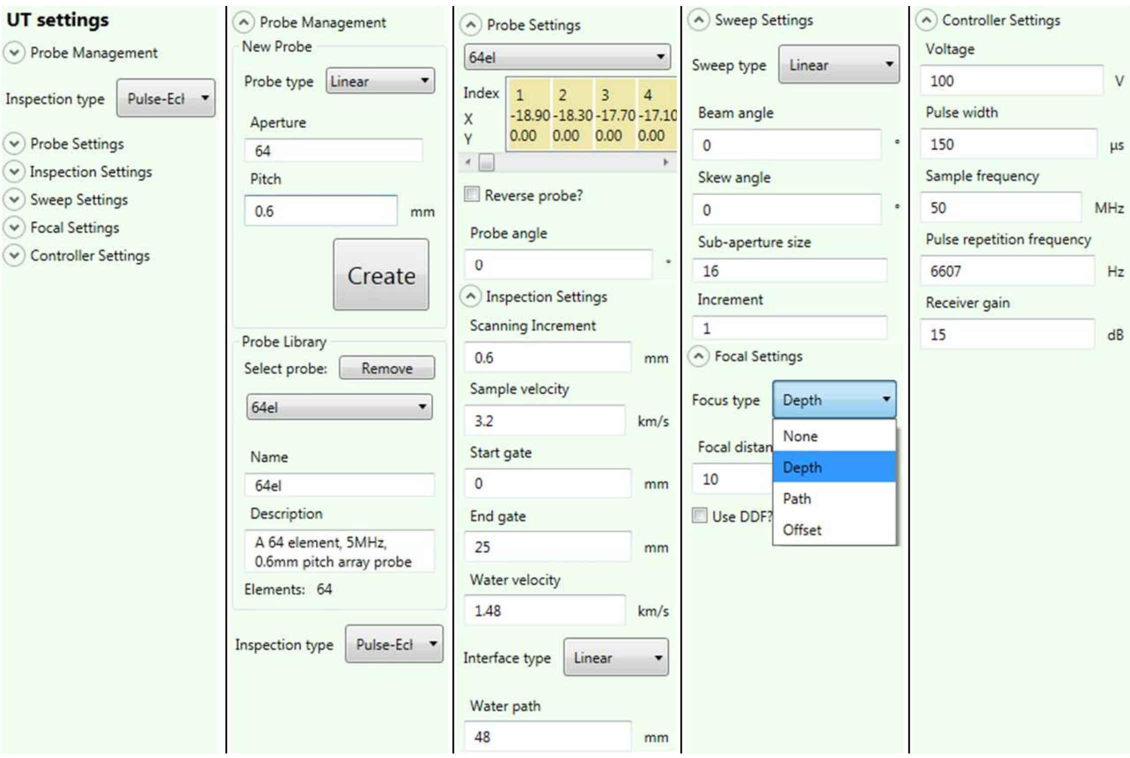


Figure 4. List of options for the complete definition of the UT settings.

The probe settings group gives a graphic representation of the probe elements and of their Cartesian coordinates, relatively 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 the 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. It 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 setup 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 get a preview of the probe profile, the real-time B-scan and the A-scans. This is very useful for optimizing 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.

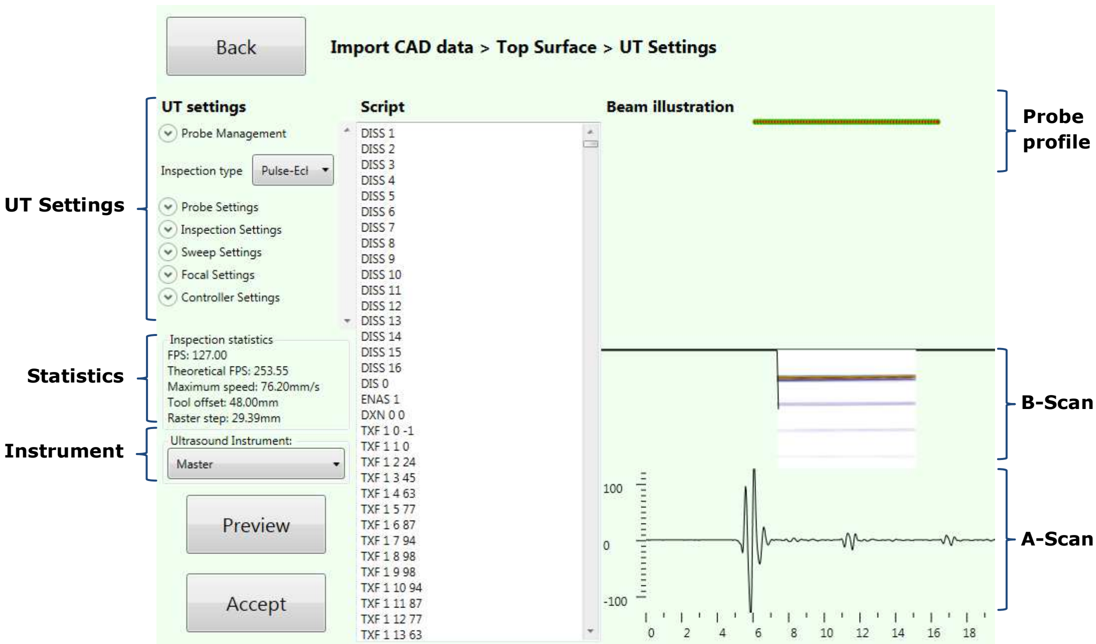


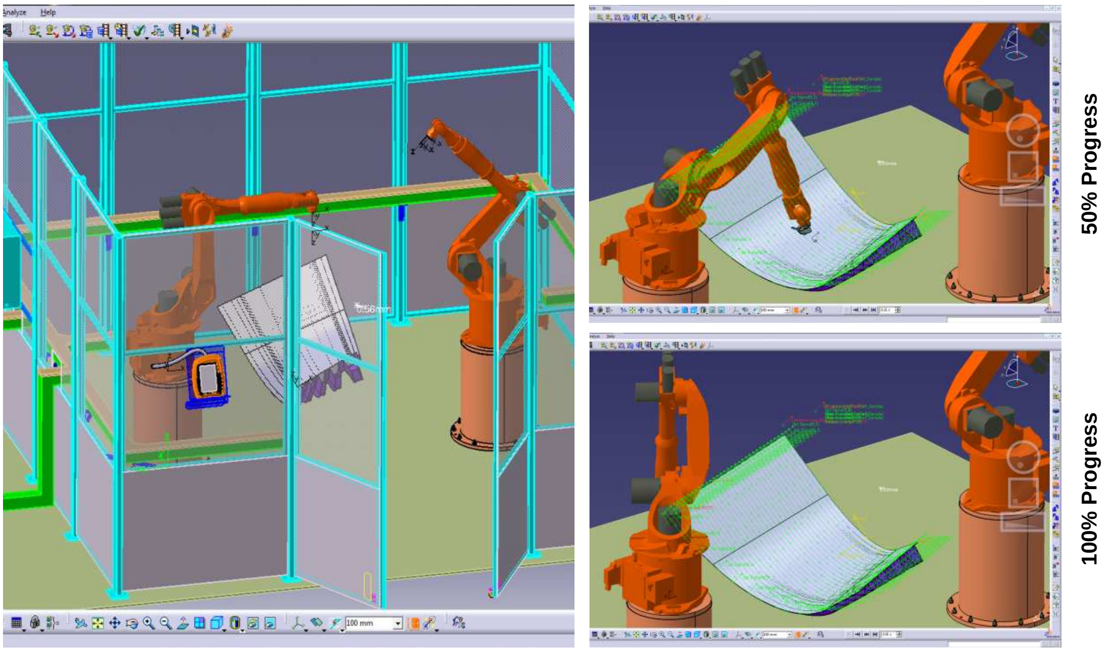
Figure 5. Preview window with the probe profile, real-time B-scan and A-scan.

The activation of the data acquisition module, to get preview information through the UT instrument, also gives the possibility to obtain statistics about the acquisition performance. The acquisition speed, in terms of 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 just considering physics, computing the time it takes for the ultrasound to travel to the back wall 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, 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.



(a) (b)

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

However, using this method for 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 off-line 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, and 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. The chosen software was CENIT-FastSurf [6], based on a Delmia platform [7].

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 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 gives 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.

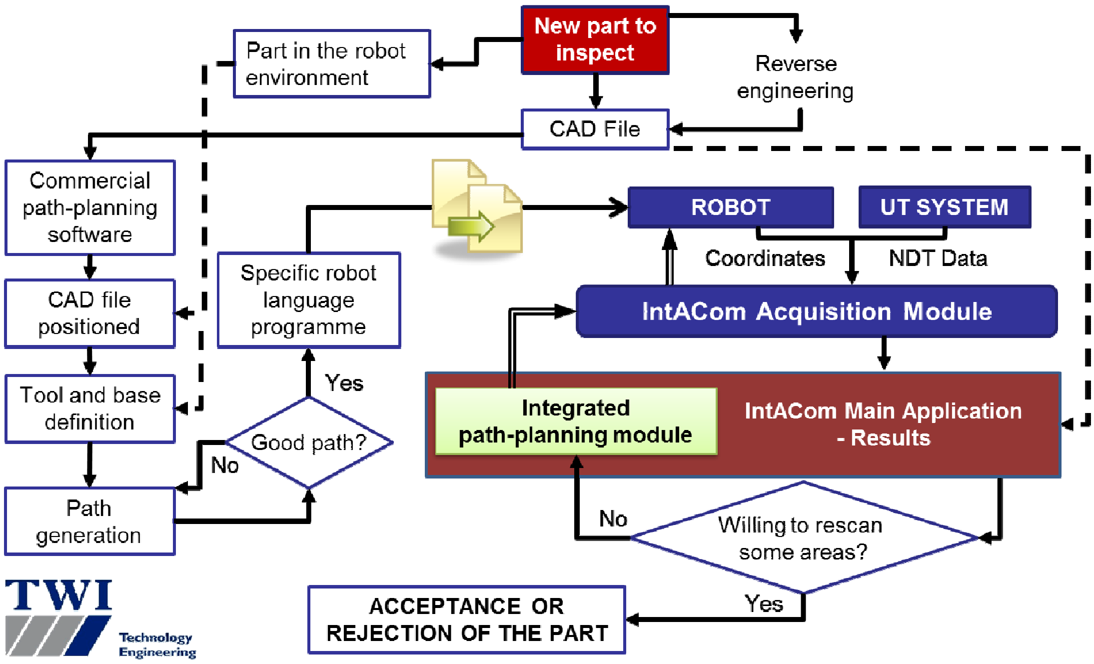


Figure 7. Schematic representation of the robotic inspection procedure.

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.

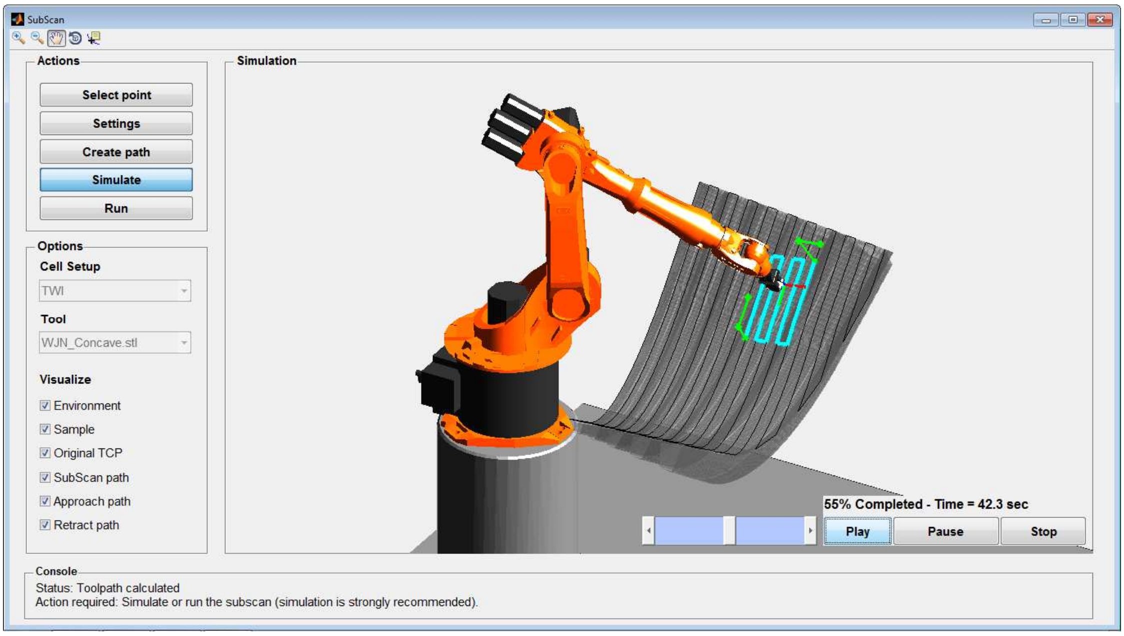


Figure 8. Screenshot of the integrated path-planning module during the simulation of the sub-scan toolpath.

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.

The process loop has been expanded to incorporate a new element, receiving communications from the server (i.e. 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 (i.e. 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 (0,0,0,0,0,0), and waiting until the “current” position matches the “demand”.

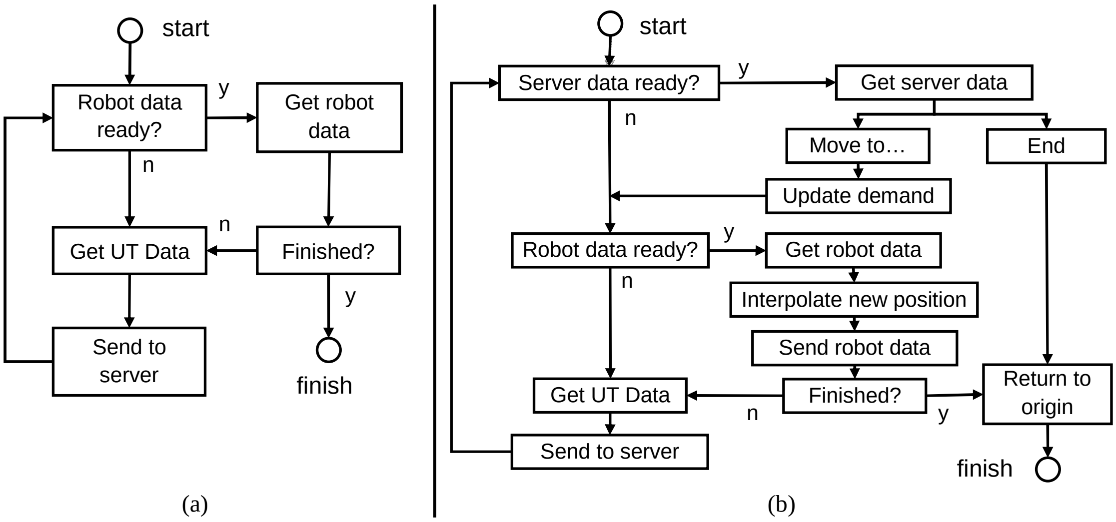


Figure 9. Process flow diagram for one-way (a) and two-way (b) robot communication.

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 m^2. It was scanned using ultrasound pulse-echo phased array inspection, using the setting parameters given in Figure 4.

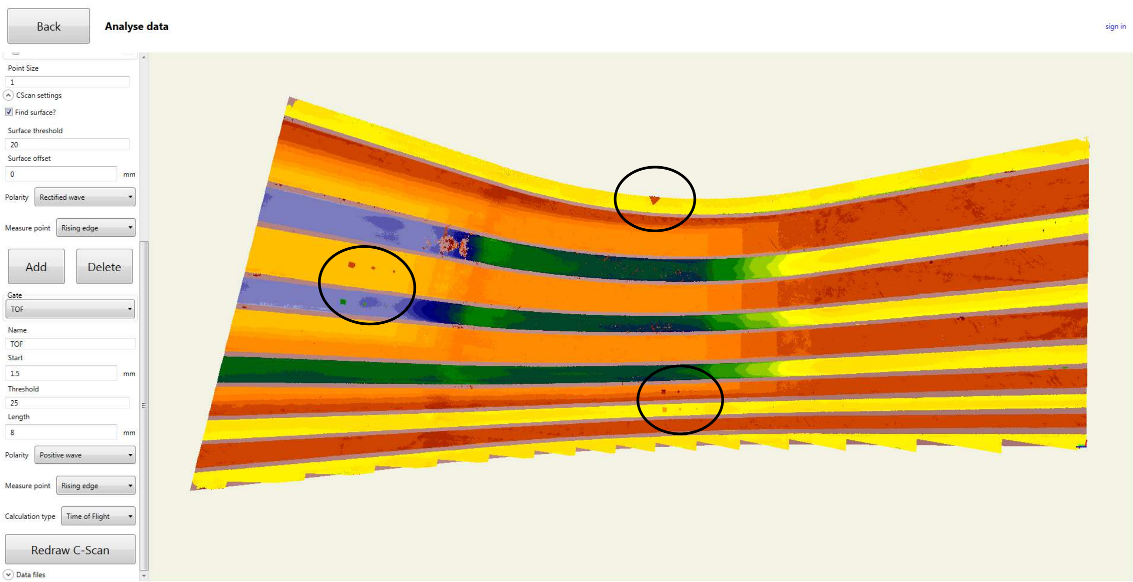


Figure 10. C-Scan of the main skin surface of the aerospace composite winglet.

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 0.6mm. The standoff between the water jet nozzle and the sample was set to 8mm. 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 to be 5mm wide and the biggest 15mm.

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 visualization of B-Scans and the 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.

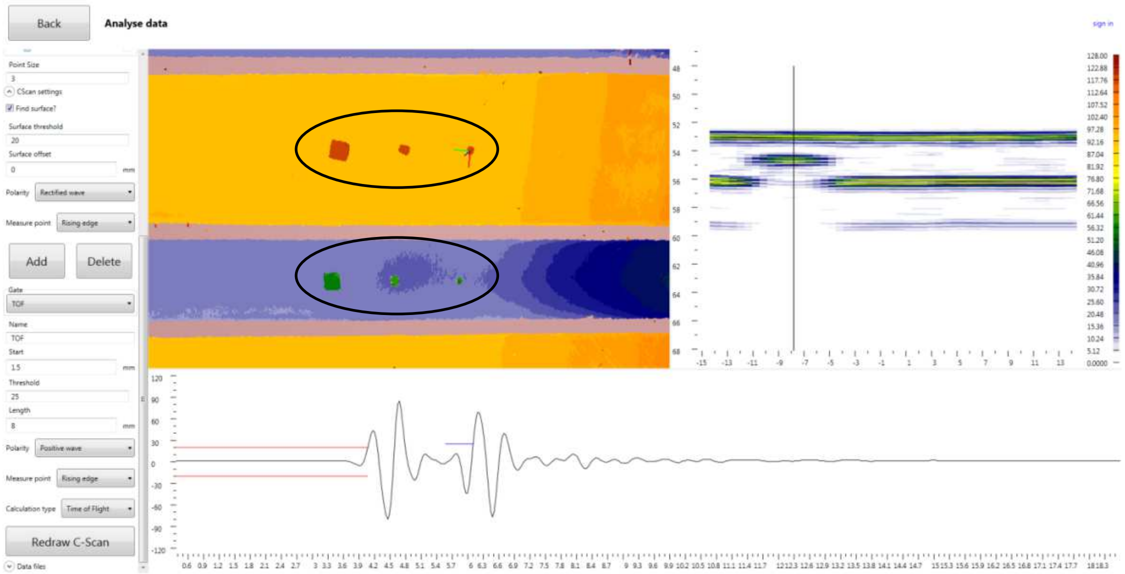


Figure 11. Close-up of one of the defected regions.

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 which is capable of inspecting complex geometries, and with a high throughput. The results presented in this paper were acquired with a 0.6mm resolution in the passive and active axes, and a velocity of 76mm/s. Scans at more typical resolutions of 1.2mm and a scan width of 29mm achieve scanning speeds of 200mm/sec, easily exceeding the '4x faster than current methods' area coverage.

Depending on the number of elements in the phased array and the maxim 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 optimization 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.

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.

Acknowledgements

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