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Flexible Integration of Robotics, Ultrasonics and Metrology for the Inspection of Aerospace Components

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Abstract. Improvements in performance of modern robotic manipulators have in recent years allowed research aimed at development of fast automated non-destructive testing (NDT) of complex geometries. Contemporary robots are well adaptable to new tasks. Several robotic inspection prototype systems and a number of commercial products have been developed worldwide. This paper describes the latest progress in research focused at large composite aerospace components. A multi-robot flexible inspection cell is used to take the fundamental research and the feasibility studies to higher technology readiness levels, all set for the future industrial exploitation. The robot cell is equipped with high accuracy and high payload robots, mounted on 7 meter tracks, and an external rotary axis. A robotically delivered photogrammetry technique is first used to assess the position of the components placed within the robot working envelope and their deviation to CAD. Offline programming is used to generate a scan path for phased array ultrasonic testing (PAUT). PAUT is performed using a conformable wheel probe, with high data rate acquisition from PAUT controller. Real-time robot path-correction, based on force-torque control (FTC), is deployed to achieve the optimum ultrasonic coupling and repeatable data quality. New communication software is developed that enabled simultaneous control of the multiple robots performing different tasks and the acquisition of accurate positional data. All aspects of the system are controlled through a purposely developed graphic user interface that enables the flexible use of the unique set of hardware resources, the data acquisition, visualization and analysis.

INTRODUCTION

The aerospace industry faces, more than other sectors, the need to inspect critical components with complex shapes in a fast fashion, without losing inspection integrity, resolution, reliability and traceability. To cope with future demand projections for modern aircrafts, it is essential to overcome the current NDT bottlenecks. NDT inspection is often performed manually by technicians who typically have to move appropriate probes over sample surfaces. Manual scanning requires trained technicians and results in a slow inspection process for large samples. It can be challenging to obtain repeatability in structures where complex setups are necessary to perform the inspection (e.g. orientation of the probe, constant standoff, etc.) [1]. Developing reliable automated solutions has become an industrial priority to speed up repetitive inspection of large numbers of components in the production chain.

Semi-automated inspection systems have been developed to overcome some of the shortcomings of the manual inspection techniques, using both mobile and fixed robotic platforms. For a number of years, the use of linear manipulators and bridge designs has provided the most stable conditions in terms of positioning accuracy [2, 3]. The use of these systems to inspect parts with non-complex shapes (plates, cylinders or cones) is widespread. Typically, they are specific machines which are used to inspect identically shaped and/or sized parts. In the spectrum of robot manipulators, some modern robots have suitable attributes to develop automated NDT systems and cope with the challenging requirements posed by the aerospace industry [4]. They include precision mechanical systems, the possibility to accurately calibrate each joint, and the ability to export positional data at frequencies up to 1 kHz. Some applications of 6-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 from many manufacturers within the aerospace sector [4-8]. In 2015, TWI produced a robotic inspection prototype system, showing a high level of integration between robotics and ultrasonic phased array instrumentation [5, 9].

Despite these previous efforts, there remain challenges to be addressed before fully automated NDT inspection of composite parts becomes commonplace. A fundamental issue with composites manufacturing compared to conventional light alloy materials lies in the process variability. Often parts that are designed as identical have deviations from CAD, and also suffer from inherent but different part to part spring-back out of the mold. This represents a significant challenge for precision NDT measurement deployment which must be flexible to accommodate these manufacturing issues. The key challenges of automated NDT inspection include generation and in-process modification of the robot tool-path, high speed NDT data collection through a variety of acquisition techniques and integration of surface metrology measurements. Given that robotic manipulators allow collection of large data volumes, new data visualization and fast data analysis methods are required to truly speed up the overall throughput of the inspection process. Additionally, the UK Research Centre for Nondestructive Evaluation (RCNDE) has identified the requirement of optimizing the tool-path generation over complex curved surfaces [10-12].

Traditionally, NDE and metrology measurements are undertaken at different stages of a product manufacture cycle using specific dedicated equipment and personnel. However, the outcomes of previous works suggest that, since both NDE and metrology processes involve direct interaction with the component's surface, motivations exists to combine these to potentially reduce overall cycle time. In addition, when considering moves towards automation of both inspection processes, it is clear that measured metrology data is an essential input parameter to the automated NDE workflow [13]. The current paper describes the outcomes of a work package developed by the University of Strathclyde in partnership with Spirit AeroSystems. This collaboration has been part of a £30M overall project (the VIEWS programme – Validation and Integration of Manufacturing Enablers for Future Wing Structures) funded through the UK Aerospace Technology Institute (ATI). A new multi-robot flexible inspection cell was established at the Advanced Forming Research Centre (AFRC, part of the University of Strathclyde). The aim of the ongoing project is to develop an automated hybrid cell demonstrator, which is capable of both ultrasonic NDT and metrology inspection. The paper describes the hardware in use, the way the instrumentation has been interfaced and the architecture of the Graphic User Interface (GUI) developed to heighten the Technology Readiness Level (TRL) up to 6 and make the inspection cell ready for future industrial exploitation.

ROBOTIC CELL AND INSTRUMENTATION

The VIEWS robotic inspection cell is shown in Fig. 1. It comprises three industrial robots, mounted on linear tracks. A custom tooling frame was purposely designed to support an external axis drive unit utilized for work-piece manipulation. The complete cell occupies an area of 103m^2 and is enclosed by fixed safety guarding with two interlocked sliding access gates. The remaining part of this section describes the robots and the external axes, the basic tooling, the metrology instrumentation, the NDT equipment and the force torque sensor. For the sake of helping the following descriptions, explanatory labels are superposed to the photo in Fig. 1 to associate a number to each robot and to indicate the external rotary axis, the target sample and the metrology instrumentation.

Robots, external axes and basic tooling

Each industrial robot is a KUKA KR90 R3100 extra HA manipulator system, a 6-axis articulated robot arm for floor/track mounting, designed to handle a load of up to 90 kg at a reach of 3100mm. Every robot comes with a KUKA KRC4 controller and user interface, which is easily programmable via a teach pendant. The robots are mounted on 200mm high booster pedestals to increase the working envelope. Each robot-pedestal assembly is mounted onto a linear track. The three linear tracks are 7m long and parallel to each other. They are KUKA KL1500-3 linear units, single-axis tracks for horizontal installation. Each track is controlled by the relative robot controller as an external axis and is used for linear traversing of the robot. The tracks allow a maximum travel of the robot carriage equal to 5.2m.

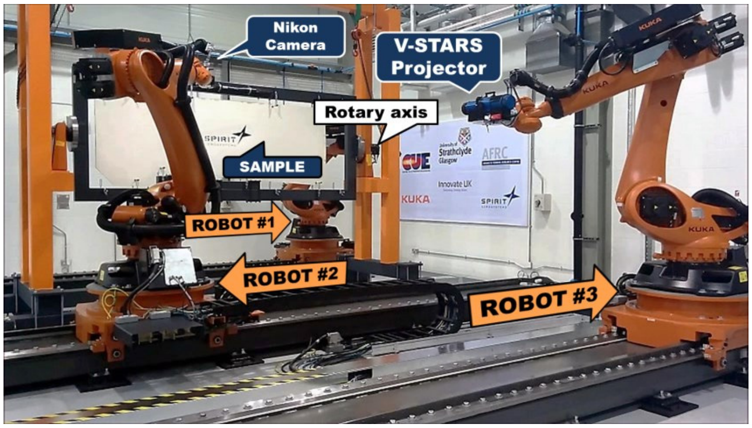


FIGURE 1. VIEWS multi-robot flexible inspection cell established at the AFRC (University of Strathclyde).

The controller of Robot #1 also controls an additional external axis drive unit (KUKA KP1-MDC750), utilized to enable the rotation of a rigid frame where the work-piece is secured. The rigid frame is supported, through the drive unit and the opposite tailstock, by a towering static frame. The latter structure and the inner frame were purposely designed and manufactured out of stiff box section steel beams to maximize the repeatability of the part positioning. Each robot is fitted with a manual tool changer comprising of a master side module, which is attached to axis 6 robot flange adapter plate, and a slave side module for connection of end effectors.

Metrology instrumentation

A feasibility study was undertaken prior to the present work to investigate a combination of NDT and metrology measurements for aerospace sub-scale components [13]. Firstly, an automated non-contact photogrammetric metrology measurement was employed to inspect the target sample for conformance of dimensions in relation to reference design (available from CAD). Upon detailed investigation, photogrammetric measurement technology was selected as the preferred solution for large scale dense metrology measurement for the aerospace industry. The V-Stars optical photogrammetric metrology system, from Geodetic Systems Inc., was chosen as the preferred system. Secondly, a robot was used to manipulate an ultrasonic phased array probe and produce ultrasonic thickness mapping of the sample. Parameters such as overall cycle time, part dimensional accuracy, robotic path accuracy and data registration were assessed. The same photogrammetry equipment was used for the present project work that represents the continuation of the initial feasibility study to higher TRL; its objective is to combine and integrate both dimensional inspection and NDT into one process in a fully automated fashion.

Photogrammetry is simply the process in which 3D coordinate information is extracted from 2D photographs [14]. Since the 3D information is not contained in a single photograph, multiple 2D images (minimum 2) are required to reconstruct the 3D world. The accuracy of the 3D information can be improved with a greater number of 2D images. Resection is the process in which the final position and orientation of the camera when a photograph is taken is computed. By knowing such resection information the 3D XYZ coordinates of a point relative to the camera can be computed through a process known as triangulation. This principle consists of mathematically intersecting converging optical rays to multiple common features from several different viewpoint 2D images. The V-Stars system used in this work is the V-Stars-N Platinum system, including the equipment shown in Fig. 2: a camera, a projector, retro reflective targets and a scale bar. The camera is a Nikon D800 digital SLR (single-lens reflex), featuring a 36.3 mega pixel Complimentary Metal-Oxide-Semiconductor (CMOS) image sensor. To reconstruct the 3D coordinates of image points, the focal length of each image must be known a priori and it is therefore set during factory calibration at a V-Stars fixed setting. Flash power to illuminate the retro-reflective targets, utilized in the coded targets and scale bars, defines the intensity of the main flash and hence the returned light from such targets. To achieve better flash direction control and power the V-Stars-N package utilizes an external “speedlight” flash (SB-400). The camera was mounted on Robot #2.

The Pro-Spot/A is a stroboscopic target projector for generation of white light markers for non-contact large scale dense metrology measurements. The Pro-Spot/A projects a maximum of 22,000 points and the light emission is triggered by the flash strobe of the imaging camera through enabling a photocell sensor placed conveniently in the proximity of the part under inspection. The projector controller allows both manual and computer control of projection power, focus and photocell enable. The Pro-Spot/A was mounted on Robot #3.

(a) (b) (c)

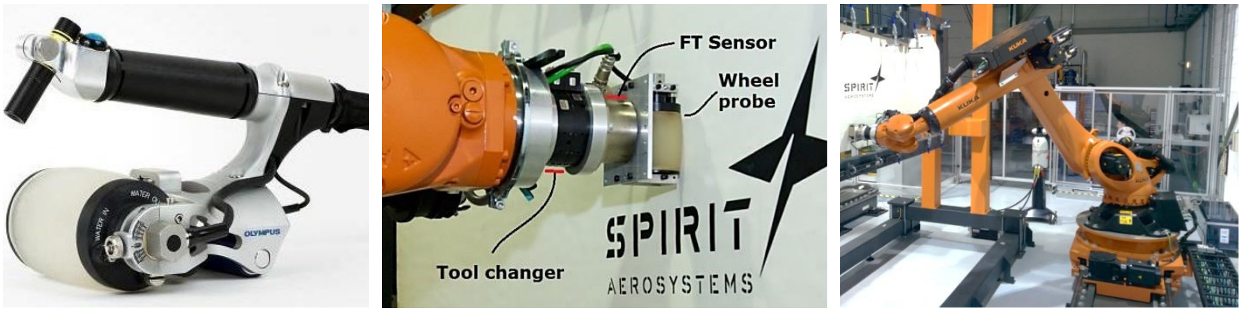
FIGURE 2. V-Stars system used in this work, including a Nikon D800 digital SLR (single-lens reflex) camera with *speedlight* flash (a), a Pro-Spot/A stroboscopic target projector (b), retro reflective targets and a scale bar (c).

A wide variety of retro-reflective targets is available to allow sensitive detection in a range of ambient lighting conditions. The strobe flash from the imaging camera illuminates the targets and ensures exposure of the targets is independent of the ambient light. Traditional targets consist of 3, 6 and 12mm diameter flat circles, each 0.1mm thick with adhesive backing. Other targets are available such as tooling, angled and spherical targets. Additionally the coded targets, shown on the bottom right corner of Fig. 2c, are retro-reflective targets that can be automatically decoded by the V-Stars software. Each target consists of a central circular target surrounded by a unique arrangement of targets. Furthermore, coded targets are required to automatically register similar points within subsequent photographs. Photogrammetry is an inherently dimensionless measurement technique and therefore requires the presence of an object of known scale and magnitude in the image dataset. With this information the distance between these known points can be computed and used to scale all other measurement values. V-Stars recommend the use of a Geodetic System precision scale-bar, with a very low coefficient of thermal expansion (0.25µm/m °K).

NDT equipment

As it was explained in the introduction, there is a need for developing NDT techniques that can rapidly scan large structures and provide quantitative data on the material integrity. Focusing on aerospace applications, the main current challenge resides in the ultrasonic inspection of composites for porosity, delaminations, foreign body contamination and fiber wrinkling. Traditional methods of ultrasonic inspection require the use of a single-point probe or a multiplexed group of probes. Ultrasonic single element and phased array (PA) testing have been integrated in several robotic inspection system prototypes over recent years [9, 15, 16]. Since the ultrasonic probes require coupling with the surface of the part under inspection, these prototypes have used purposely developed water jet nozzles that embed the ultrasonic transducer and provide a water column for the transmission of the ultrasonic beam.

However, the creation of water jet coupling for large PA probes requires water columns with large section, thus big flow rates (up to 40-50 liter/min) being pumped to the end effector of the robot manipulator through suitable flexible hoses. To avoid waste, used water should be collected, filtered and reused through recirculation circuits. Water columns longer than 20mm allow accommodating significant stand-off variability that can be given by inaccurate part positioning within the robot work envelope, inaccuracies in the calibration of the robot base reference system and/or of the robot tool central point. Nevertheless, a long water column makes it difficult to maintain stable water flows, free from bubbles and turbulence, required for good ultrasound transmission. Moreover, some manufacturers of composite materials do not sympathize with the exposure of part surfaces to water jets, since the humidity absorption can reduce the performances of composite materials (e.g. fatigue strength) and also compromise the joints, leading to a reduction in the bond strength [17, 18].



(a) (b) (c)

FIGURE 3. RollerFORM® in its original configuration (a) and mounted onto the robot through a support (b) and picture of Robot #1 during the scan of a composite aerospace wing sample (c).

The robotic cell described in this work has the capability of performing ultrasound inspection, through ultrasonic arrays housed within a rubber coupled wheel sensor. This approach was originally developed by *NDT Solutions Ltd* for new manual inspection techniques of large components [19]. It removes the need for a free water column. The RollerFORM® phased array wheel probe by Olympus is used. The wheel is made of a material that closely matches the acoustic impedance of water. It requires only a very thin and volatile film of water being sprayed on the part surface to optimize the coupling with the rubber tire of the wheel probe. The RollerFORM comes with an ergonomically designed handled to allow manual inspection, as it is shown in Fig. 3a. In our integration, the wheel probe was removed from the handle and mounted to Robot #1, through a purposely designed support (see Fig. 3b). The embedded phased array probe is a 5MHz, 64 element, 0.8 mm pitch transducer.

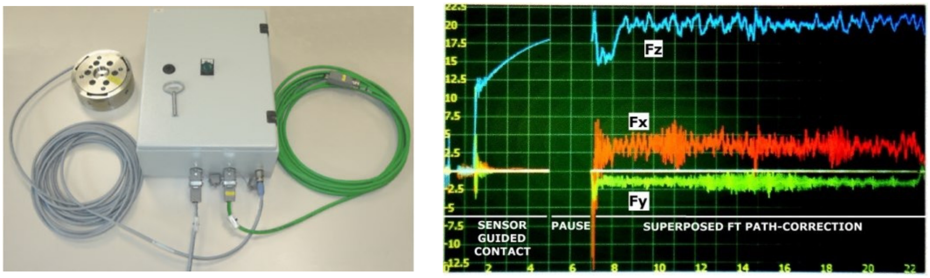
The wheel probe was used with an Olympus OmniScan® phased array instrument, in the initial stage of this research; however the limited memory of the portable device did not allow collection of large high-resolution C-scan images, which is essential for the inspection of large aerospace components. Moreover the data acquisition rate of the OmniScan represented a bottleneck, limiting the maximum robot scanning speed. A customized instrument was designed, commissioned and procured through *Diagnostic Sonar Ltd*. This is herein referred as *FIToolbox* instrument. The instrument enables high data rates by harnessing the flexibility of Field Programmable Gate Arrays (FPGAs) in a standard PC platform [20]. The FPGAs (DSP-focused Virtex-5 SX95T) can be reconfigured under software control to provide a flexible platform, handling applications from array imaging to multi-channel automated inspection systems. The FIToolbox system has been developed with off-the-shelf components, combining 64 channels of high-speed analogue acquisition with a high performance FPGAs for real-time, deterministic processing. It is a 64Tx/64Rx system that interfaces to an ultrasonic array probe via multi-channel pulser-receivers with custom FPGA code developed using LabVIEW. The instrument enables high performance multi-channel ultrasound acquisition and processing, while being flexible enough to address a wide range of applications. The data transfer rate of high performance phased array receivers is often limited by the interface between the device and the controlling computer. This is not the case for the FIToolbox, where National Instrument MXI-Express hardware enables direct communication with computer memory via the PCI Express bus that provides the highest bandwidth of all PC I/O buses [21]. The FIToolbox can stream data to the computer up to 1.6 GB/s, via a 50m fiber optic cable. Figure 3c shows the FIToolbox instrument mounted to the right hand side of the carriage of Robot #1.

Force Torque sensor for accurate real-time robot path correction

Since the RollerFORM contact probe is used for NDT scan, instead of a water jet coupling, it imposes limitations on the stand-off variations between the probe and the part surface. The rubber tire needs to be maintained in contact with the part surface for the entire duration of the inspection and a fairly constant coupling force has to be maintained between the tire and the part. The probe, in the configuration shown in Fig. 3a, is designed to work with the range of coupling forces produced within the region of comfort of the operator arm and hand. The operator force that produces a good adherence between the rubber tire and the part surface is generally in the range of 15-25 N.

A variation of $\pm 3mm$ of the Tool Centre Point (TCP) in the direction orthogonal to the part surface produces a significant variation in the tire compression and in the normal-to-surface force (F_Z).

This is critical when the RollerFORM is manipulated by the robot, since an out of range compression can overload the wheel probe and the part, leading to failures. Therefore, Robot #1 was equipped with a Force Torque (FT) sensor, mounted between the slave side of the tool changer and the wheel probe support (Fig. 3b). An ATI-NET-GAMMA-IP65 sensor system is used [22], comprising: the FT Sensor, the FT controller box, the energy supply, cabling and control software add-on for KUKA KRC4 robot controllers. The hardware components are shown in Fig. 4a.



(a) (b)

FIGURE 4. Force torque sensor package (a) and monitor of the force components, as it is displayed by the robot pendant (b).

The FT sensor provides the three Cartesian components of the load (F_X, F_Y and F_Z) and the three torques (T_X, T_Y and T_Z). After calibrating the FT sensor, to neglect the force components produced by the wheel probe assembly, the value of 20N was chosen as a target average value for F_Z; this value ensures constant adherence of the wheel tire with the sample surface during the scan, when variability within ±1mm in the position of the wheel along the normal direction can be observed. Additionally, the torque values can be monitored; null torque values ensure normal orientation of the PA probe with respect to the scanned surface, thus maximum amplitude of the ultrasonic signal. The FT control configuration suitable to support the wheel probe based ultrasonic PA inspection is constituted by two consecutive phases of control. The first phase enables sensor guided movement of the robot arm to approach the part surface and establish the initial contact between the wheel probe and the part. In this control type, the robot is made move along the direction normal to the target point of contact. As soon as an increase in the value of F_Z is detected, the FT feedback starts reducing the speed of the robot until the target coupling force is reached and the robot stops. The target contact force was set to 18N. A pause of 2sec was introduced to allow damping of any part vibrations produced by the initial contact. The second control phase enables the superposed FT real-time path correction. The FT feedback is used to apply corrections to the predefined robot path, in order to maintain the 20N coupling force during the data acquisition. Figure 4b shows the plot of the force components for one pass of the inspection raster tool-path, comprising the initial contact and the superposed path-correction phase.

SYSTEM INTEGRATION

The robotic cell was designed to allow a great deal of flexibility. The safety control configuration has two safety zones defined: Zone 1 (comprising Robot #1 and Robot #2 and associated equipment) and Zone 2 (comprising Robot #3 and associated equipment). The current configuration joins both of the above zones together for a single complete cell – encompassing all cell equipment. In the future, a safety guard can be installed between the linear track of Robot #2 and #3 and two independent safety zones/cells can be realized.

In order to allow high throughput metrology and NDT inspection and enable the high level of automation envisaged by our work, fundamental software was developed to establish robust communications between the robot controllers, the photogrammetry equipment, the NDT instrumentation and the server computer. C# and C++ programming language were chosen to develop crucial software components. These languages allow a low level control of the communication strategies and are suitable to develop data acquisition algorithms that run in a reliable manner. The crucial modules were compiled in Dynamic Link Libraries (DLL) or executable packages and encapsulated into a purposely developed seamless graphic user interface (GUI). The GUI was developed through Matlab and designed to provide a seamless interface, through which all aspects of the system (setup preparation, testing, data collection, data collection and analysis) can be managed with robustness and ease. It gives the possibility to define the global settings, necessary to operate the system. As many variables as possible were parameterized, to enable high level of flexibility for immediate and future exploitations. The GUI enables the initialization of NDT projects, a photogrammetry projects and a jointed NDT & Photogrammetry projects, to perform simultaneous NDT and photogrammetry data acquisition with high throughput. The test of the robot paths and the data acquisition require the use of the system hardware. Given the complexity of the system and the number of instruments that come into play, the software is equipped with a preliminary resource checking capability that helps the user to check all instruments and communications work correctly, before the robotic tasks can commence.

Robot cell communication links

Figure 5 shows the robot cell communication links.

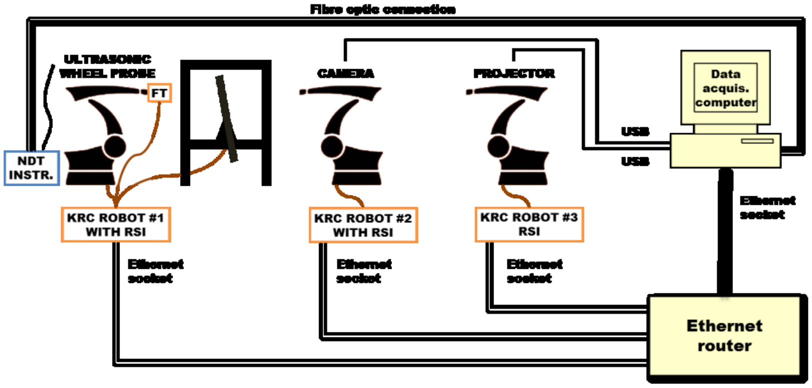


FIGURE 5. Layout of robot cell communication links.

Full communication with the robot controllers is required to automate the execution of the robot programs, developed by off-line path planning software, and launched via the robots' teach pendants. This can be done by interfacing the robot controllers to the server computer through a peripheral device that transfers the digital statuses of the digital robot outputs to a USB port of the computer and enables the computer to send triggering digital flags to the digital robot inputs. However, this approach requires a lot of wiring and is poorly scalable to systems with numerous robots. Moreover an extra Ethernet link to each robot would be required to retrieve the current robot positional feedback, necessary to encode the inspection data. Working with KUKA robots, the transmission of positional feedback through Ethernet socket is allowed by a software add-on application known as Robot Sensor Interface (RSI), installed into the robot controllers. Recent applications have also demonstrated the use of RSI to establish a double direction communication, to trigger the progress of the execution of programs and send target command positions to drive the robot arms from the server computer [12]. Therefore, the RSI add-on was installed on all robot controllers to support the link with the server computer, through an Ethernet router, as shown in Fig 5.

Communication software was developed to enable simultaneous Ethernet communication with the three robots of our configuration. The key functions of the robot communication code were exposed through a DLL library, herein referred as *Robotic DLL*. The DLL was designed to get feedback parameters from the robots, to monitor the status of the running robot programs and trigger the progress of the robotic tasks from the server computer. The managed C++ language (C++/CLI) was chosen to develop the Robotic DLL; it is suitable to develop crucial communication and data collection algorithms that run in a real-time reliable manner. The C++/CLI programming language offers the programmer specific features to avoid the periodic, automated creation and disruption of allocated memory, known as garbage collection (GC). If GC is not controlled, it can lead to unexpected drops in software performances [23, 24].

Photogrammetry

Nikon provides C# based Software Development Kit (SDK) to allow integration of their products in research and development applications. The SDK for the D800 camera allows control of most of the camera settings, including shutter speed, aperture, and ISO sensitivity. To manage the camera from our software GUI, the SDK functions need to be complied into a 64bit DLL that can be loaded into the GUI. Unfortunately, the Nikon SDK only supports x86 platforms and is incompatible with the x64 architecture, which is the architecture of our overall system. A common solution to use a 32bit DLL in a 64 bit program is to wrap the 32bit DLL in 32 bit executable file and use an intercrosses communication method to send and receive data from the DLL.

The Pro-Spot/A projector connected to the computer through a USB serial port. By default, the projector is controlled using a V-Stars program. However, to control the projector from third-party software, a virtual TCP/IP communication should be used to send some predefined command ASCII strings to the V-Stars program. This requires installing and running the V-Stars program on the server computer. To simplify the process it was decided to replicate the communication protocol between the projector and the V-Stars program into a purposely developed C++ code that can directly communicate with the projector. Therefore, a standalone 64bit DLL was developed, to control the projector independently from the V-Stars program. The DLL functions make it possible to setup the projector and trigger it whenever required. Using this DLL it is also possible to monitor all the ASCII strings arriving to the computer from the projector and make sure it is working as expected, capability that does not exist when using the default V-Stars program.

NDT Inspection

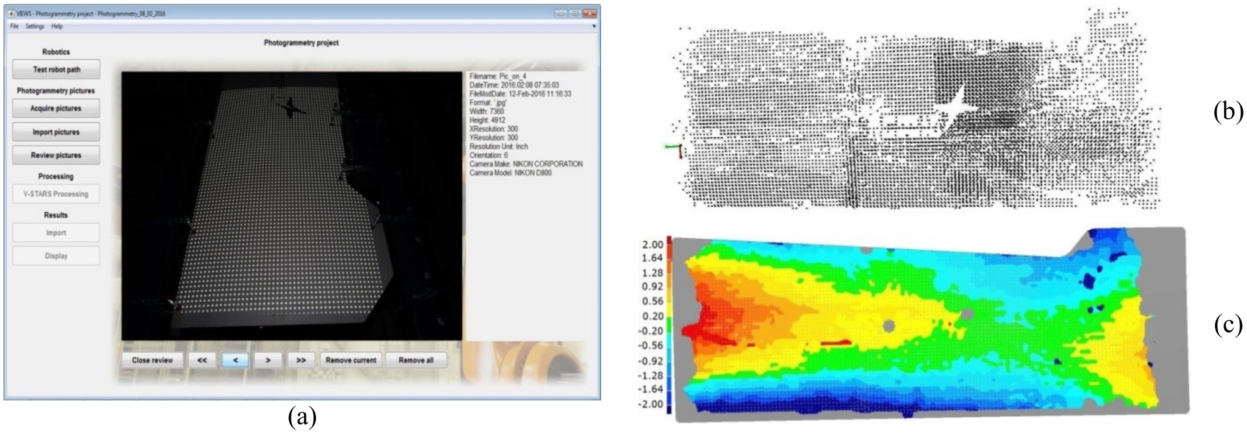
The FIToolbox multi-channel pulser-receivers are controlled through specific LabVIEW based code, provided by the system developer (DSL Ltd). The equipment native software architecture has been designed to allow for customization. When combined with the modular and scalable hardware, this ensured that the system could be optimized for our specific configuration. Access to the source allowed the fulfillment our research objectives. Our work focused on developing a software solution to integrate the NDT instrument with Robot #1.

The resulting software is fundamental to enable simultaneous collection of the robot positional packets, through the RSI Ethernet socket, and the PA data from the FIToolbox, through fiber optic connection to the computer PCI Express bus. Both data streams are time stamped with the same clock. This was achieved through embedding the Robotic DLL functions into the native FIToolbox controlling software. The NDT module of the GUI contains the post-processing algorithms, necessary to extract the desired information from the raw inspection results. The fundamental phase of the post-processing data extraction regards the encoding of the ultrasound data through the positional information received from the robot controller. Since every A-scan waveform received from the phased array has an associated time-stamp, recorded at the moment of acquisition, the robot positional packets are interpolated to associate optimum positional coordinates. This represents the basis of the display of three-dimensional C-scan maps.

RESULTS

This paper focused on the description of the integration work undertaken to produce a robotic cell with photogrammetry and ultrasonic inspection capabilities. This section draws the paper to an end by presenting examples of results originating from the data acquisitions performed through the robotic system. Figure 6a shows the screenshot of the GUI during the review of the photogrammetry pictures acquired for the geometry inspection of the 3m^2 composite wing sample, with the setup shown in Fig. 1. The robotic system acquired 48 photogrammetry pictures that were post-processed through the V-Stars software, producing the point cloud given in Fig. 6b. Thus, a deviation from CAD map was computed, resulting in the map shown in Fig. 6c. The deviation of the part from the reference CAD model resulted within a range of ±2mm.

An ultrasonic PA scan was carried out through Robot #1, manipulating the wheel probe at a scanning speed suitable to obtain a scan resolution of 1.6mm. Figure 7 shows the data analysis module of the NDT project, accessible from the “Analyze” module of the NDT project. The NDT data analysis module is packed with features that facilitate the analysis of the NDT dataset. It comprises the C-scan 3D plot, the B-scan and T-scan frames and the A-scan waveform plot, with the possibility of customizing the displayed entities and the color pallet. Flexible post-process algorithms have been implemented to enable time gain correction (TGC) and ultrasonic gating to create amplitude and time-of-flight (TOF) C-scan maps. The user can move the cursor over the C-scan, B-scan and T-scan plots to interactively refresh them according to the areas of interest. Future versions of the module will incorporate features for assisted defect recognition and sizing tools to facilitate identification and measurement of flaws.



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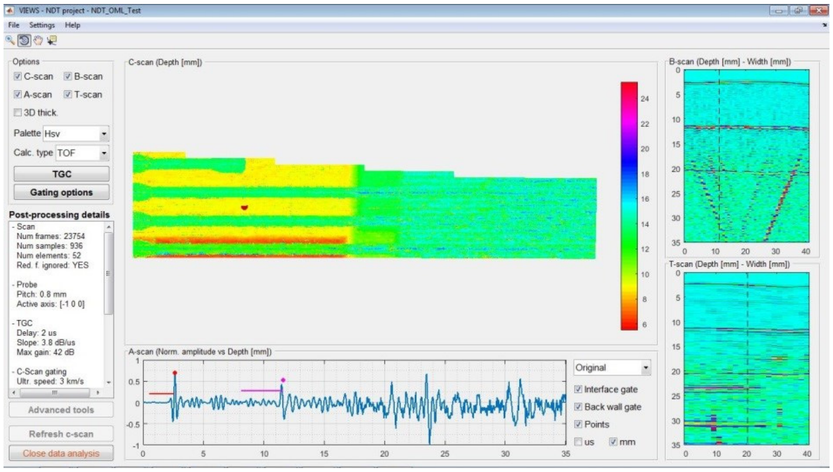
YResolution: 300
Resolution Unit: Inch
Orientation: 6
Camera Make: NIKON CORPORATION
Camera Model: NIKON D800

(a) (b) (c)

FIGURE 6. GUI during the review of the photogrammetry pictures (a), post-processed point cloud (b) and deviation to CAD (c).



☑ C-scan ☑ B-scan
☑ A-scan ☑ T-scan
☐ 3D thick.
Palette Hsv
Calc. type TOF

Post-processing details
- Scan
Num frames: 23754
Num samples: 936
Num elements: 52
Red. f. ignored: YES
- Probe
Pitch: 0.8 mm
Active axis: [-1 0 0]
- TGC
Delay: 2 us
Slope: 3.8 dB/us
Max gain: 42 dB
- C-Scan gating
Ultr. speed: 3 km/s

Original
☑ Interface gate
☑ Back wall gate
☑ Points
☐ us ☑ mm

FIGURE 7. Data analysis module.

CONCLUSIONS

This paper presented the latest progress of a new phase of the research applied to the photogrammetric and ultrasonic inspection of composite aerospace components. A multi-robot flexible inspection cell was developed to take the fundamental research and the feasibility studies to higher technology readiness levels, for future industrial exploitation. The robot cell was equipped with high accuracy and high payload robots, mounted on 7-meter tracks, and an external rotary axis. A robotically delivered photogrammetry technique was developed to assess the position of the components placed within the robot working envelope and their deviation to CAD. Offline programming was used to generate a scan path for phased array ultrasonics testing which was implemented using high data rate acquisition from a conformable wheel probe. Real-time robot path-correction based on force-torque control ensures optimum ultrasonic coupling and repeatable data quality. New communication software was developed to enable simultaneous control of multiple robots and manage the acquisition of accurate positional data. All aspects of the system are controlled through a purposely developed graphic user interface that enabled the flexible use of the unique set of hardware resources, the data acquisition, visualization and analysis.

Future work will address the following aspects: maximization of the data acquisition rate, enabling simultaneous NDT and photogrammetry data acquisition with high throughput and automatic defect recognition. A high level of automation will be achieved through enabling automated surface generation from photogrammetry scanning, followed by automatic scan-path generation. Ultrasonic Full Matrix Capture (FMC) and Total Focusing Method (TFM) will provide potential for exploiting the NDT instrument high acquisition rate. Optimization of the new visualization techniques for 3D data sets will lead to powerful new tools for defect analysis.

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