Camera Encoded Phased Array for Semi-Automated Inspection of Complex Composite Components

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ABSTRACT
This paper introduces a new wireless solution that permits performing accurate and traceable ultrasonic scans of components with complex geometries using a hand-held scanner. The system integrates an array of 3D cameras that track the position of the hand of the inspector with a high-performance PAUT instrument to provide accurate, high-resolution C-Scans on any component. This paper provides results of hand-held scans on complex composite parts, and explores how the solution compares with traditional semi-automatic and automatic systems in terms of setup, ease-of-use, performance, productivity, and cost.

Keywords: wireless encoding, 3D camera encoding, Phased Array of composites, semi-automated inspection.

INTRODUCTION
A basic premise in project management is called the Triple Constraint or Iron Triangle of Time-Quality-Cost. Experienced project managers like to remind their supervisors or clients that they can choose fast, good, or cheap, but only two at a time.

A common solution to push the boundaries of this triad is by increasing the level of automation in a process. A higher degree of automation is typically associated with more output, better quality, and, despite the initial higher cost, a cheaper alternative for large-volume production. For NDT in manufacturing, this has meant the introduction of in-line and off-line integrated inspection systems with increasing degrees of sophistication. These systems can be run by line operators without NDT expertise, and still deliver permanent records of inspection to demonstrate compliance to a customer or regulator. In these manufacturing environments, manual inspections are increasingly relegated to MRO (Maintenance, Repair, Overhaul) processes that are characterized by low volumes and complex or difficult to access components. The findings and quality of records on a manual inspection will be ultimately dependent on the quality, training, and experience of the NDT practitioner.

In these manufacturing environments, the challenge arises when quality inspections and a permanent record is demanded, but the complexity of the component or limited production volumes do not justify the investment in an automated inspection system. This problem is compounded when there is limited access to qualified and experienced NDT inspectors to perform the work and certify the results.

The solution many times involves semi-automated scanners, crawlers or similar devices that are mounted on the part for complete or partial scanning. These systems are typically limited to simple-geometry parts since they do not have the mechanical flexibility of robots, and the ability to provide accurate 3D encoding to match the inspection results with the actual geometry of the component. Also, setup, inspection, and interpretation still require trained NDT personnel.

This paper introduces an innovative solution to perform advanced ultrasonic inspections on complex parts with very limited setup costs and investment. The system integrates an advanced phased array ultrasonic system (PAUT) with an array of infrared (IR) vision cameras to provide three-dimensional (3D) spatial location of the probe on manual inspections. The system provides a complete C-Scan of the part with sub-millimeter positioning accuracy on very large parts, completely eliminates the need for mechanical encoders, and can be used on parts of any shape.

This encoding technique can also be used to simplify an upgrade from conventional UT to advanced PAUT on an existing inspection cell by eliminating the need to integrate the ultrasonic instrument with the line robot or gantry.

The results presented are from actual systems used for inspection of Carbon Fiber Reinforced Polymer (CFRP) used in aerospace. The same technique can be used for inspection of forgings, or other large components of any shape.

The system and technique was originally developed by Tecnatom S.A. in Madrid (Spain), and has been adapted for the North American market by Innerspec Technologies Inc. in Forest VA (USA). It is currently commercialized under the WiiPA name in Europe, and CAMUS 3D in North America.

CAMUS 3D
Camera Aided Ultrasonic System

DESCRIPTION OF EQUIPMENT

Figure 1 shows a block diagram of the main components of the inspection system.

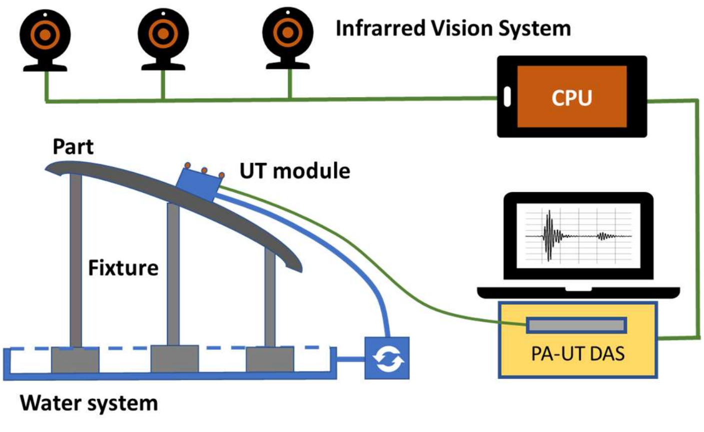

Figure 1. Block diagram of the UT inspection system based on infra-red visual tracking.

The system includes:

- **Data Acquisition System (DAS)**. The PAUT instrument is based on Tecnatom's SONIA platform and InspectView software.
- **UT Assembly**. Includes a 32 or 64 element linear Phased-Array probe, custom wedges for mechanical contact to the part surface, a bubbler for ultrasonic coupling in local immersion, a device for ergonomic handling of the assembly, and the IR markers for spatial location of the complete assembly (small spheres reflecting light in the infrared spectrum).

- **Infrared Vision System**. This system contains several infrared cameras (from 3 to 20), depending on the size of the part inspected. These cameras are placed in the cell so at least three cameras have always a direct line of vision to the UT Assembly. The special triangulation algorithms processed in real-time by a central processing unit (CPU) generate the 3D positioning coordinates of the UT Assembly, which are transferred to the DAS to generate the C-Scan of the part.
- **Water Management**. The bubbler holding the transducer is continuously supplied by a small water flow for proper ultrasonic coupling. A tray collects the overflow which is filtered and pumped back to the UT Assembly.
- **Part Fixture**. Holds the part and provides mechanical stability during the inspection process. The Part Fixture also includes IR markers for correct mapping of the UT Assembly on the part.

The inspection technique is a linear Phased-Array UT Pulse-Echo (PAUT-PE) with custom transducer and wedges to adapt to any of the geometries that are found in production parts (inner/outer radius, ramp, basins, etc.). The sensors can run at different frequencies (typically 3.5 or 5 MHz) to meet the inspection needs.

Figure 2 shows an example of a standard implementation of the solution in an industrial environment. In this configuration, the system has eight IR cameras installed at the top of a metallic structure to ensure that the UT Assembly is followed by at least three cameras at all times. The structure also permits wiring and piping for the UT Assembly and holds the DAS and screens used by the inspectors to monitor the results.

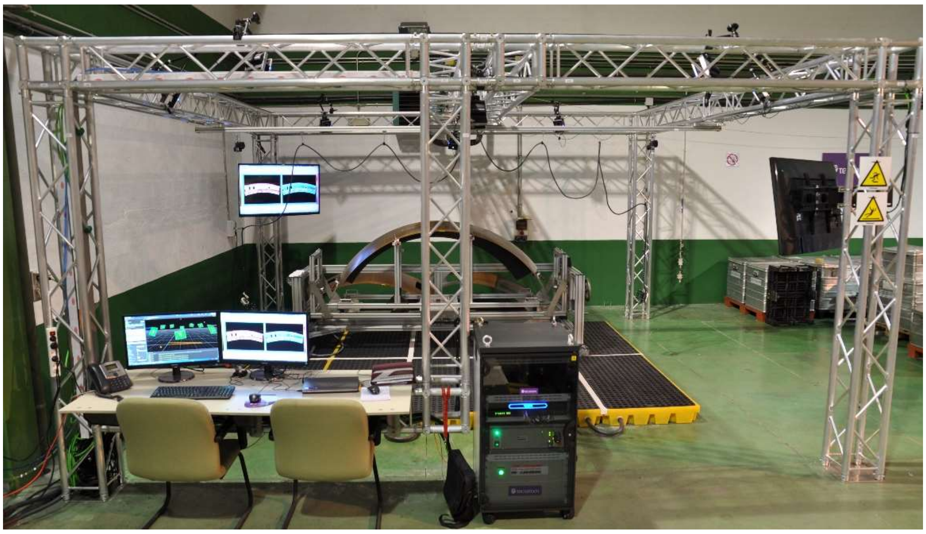

Figure 2. Industrial implementation of a inspection cell based on IR visual tracking.

INTEGRATION CHALLENGES AND SOLUTIONS

UT inspection and IR 3D scanning are known technologies that are frequently used independently. This section covers the integration challenges and the custom solutions developed for this innovative application.

- **Ultrasonic Coupling.** There are several coupling methods to perform PAUT-PE inspections, in manual or semi-automated inspections. A probe bubbler with custom wedges was the method selected because of its reliability and productivity. Use of dry-coupling techniques is currently being investigated but has not yet been implemented due to severe limitations for inspection of curved shapes.
- **Ergonomics.** Considering that the inspection is performed manually, the ergonomics of the Part Fixture and UT Assembly are critical to provide a safe and productive work environment. Each part needs to be properly analyzed prior to installation to set up the right height of the fixture and monitors, and permit comfortable scanning of all surfaces.

Figure 3. Detail of ergonomic implementation of the IR markers on the UT module.

- **Human-machine Interaction.** Together with ergonomics, proper design of the human-machine interface is critical for safety, reliability, and productivity. The CAMUS 3D interface has been optimized to provide real-time and easy-to-interpret C-Scans with an accurate depiction of the location of the probe. The system includes controls so the operator can easily pause and resume the inspection without losing data, and re-scan and overwrite areas of the part without compromising the integrity of the results. The equipment also permits merging the information from several operators working on the same part, or even having several inspections on different parts in the same inspection cell.
- **Latency Control.** One of the key integration components with IR tracking systems is the time required by the IR system to process the spatial coordinates and transfer the information to the UT instrument, which can take tens of milliseconds. Even though manual inspection speeds are typically low (less than 150 mm/sec) this latency can cause hysteresis phenomena that will distort the C-Scan results. To avoid this problem, especially when the IR tracking system is mounted on faster robotic lines, the technique requires software controls designed specifically for integration between the IR and UT systems.
- **Resolution, Accuracy, and Repeatability.** UT inspection of parts with complex geometries typically requires resolution, accuracy, and repeatability between 0.1mm and 1mm. These requirements involve good mechanical characterizations of the component, the Part Fixture, the UT Assembly as well as fast and accurate calibrations of the IR cameras with three-point correction tools. Fast calibration is also important to quickly resume work if there is an undesired movement on the part, cameras, or Part Fixture.
- **Lighting.** IR tracking systems can be affected by direct or reflected infrared light from natural or artificial sources causing location errors. To avoid these errors, IR markers need to be set in a pattern that is easily tracked by the vision system. This is also important during the design of the inspection cell so the cameras are not affected by light sources or reflections from outdoor windows, mirrors, lamps, etc.
- **3D Analysis and Rendering.** Since CAMUS 3D is primarily used to scan complex geometries, it is paramount that the results are also analyzed and provide interpretation in easy-to-interpret 3D renderings. InspectView software provides tools to incorporate CAD data and overlay the inspection results on the imported file. In addition to this, all UT results are analyzed based on the actual volumetric configuration of the part for proper sizing and interpretation of the results. The inspection data can be presented in 3D and 2D formats for analysis by the inspectors based on different code requirements and personal preferences. Figure 4 shows one of the available tools for 3D rendering and analysis.

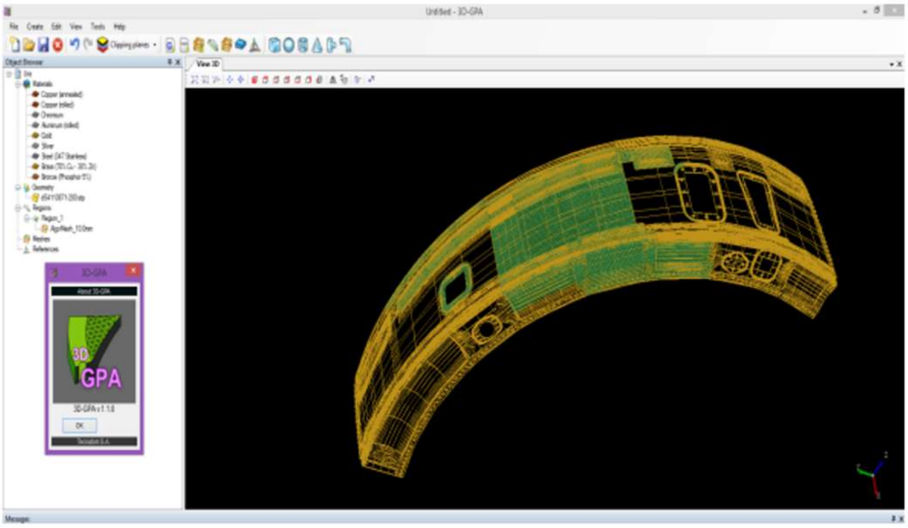

Figure 4. Software tool to adapt complex geometries for 3D inspection environment.

- **Combined Part Records.** InspectView software for CAMUS 3D is designed so all the files from inspections of one part can be merged into one single Part Record. This is especially relevant when the part has been inspected at different times using probes and wedges adapted to the geometry of different sections. A typical example is found in the inspection of parts combining flat surfaces and radii (either inner or outer) that are common in aerospace. In these cases, having different scans combined into one Part Record facilitates final analysis and record keeping.

RESULTS

Figures 5 and 6 show some examples of C-Scan records produced with a CAMUS 3D system. Data from CFRP reference blocks with artificial defects are shown. Images show two magnitudes: signal amplitude and sound path. Both images are of high quality and homogeneity.

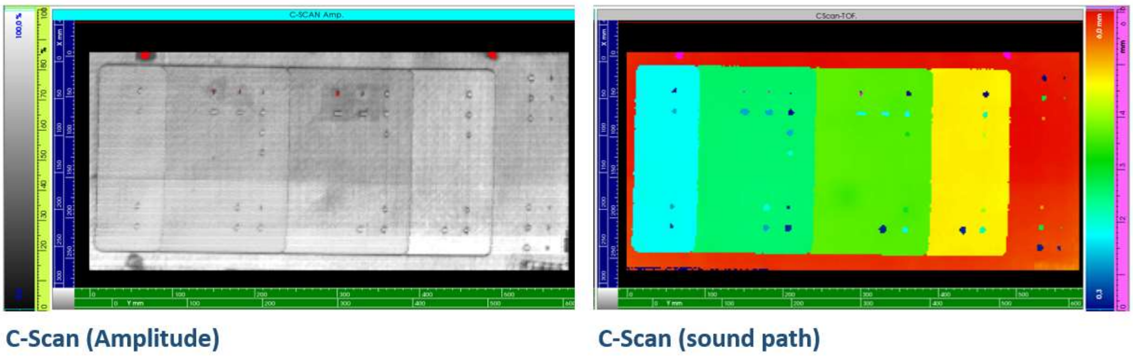

Figure 5. Comparative view of C-Scan records, both in amplitude and sound path. Obtained with the CAMUS 3D inspection system on a CFRP reference block (pulse-echo technique, 5 MHz)

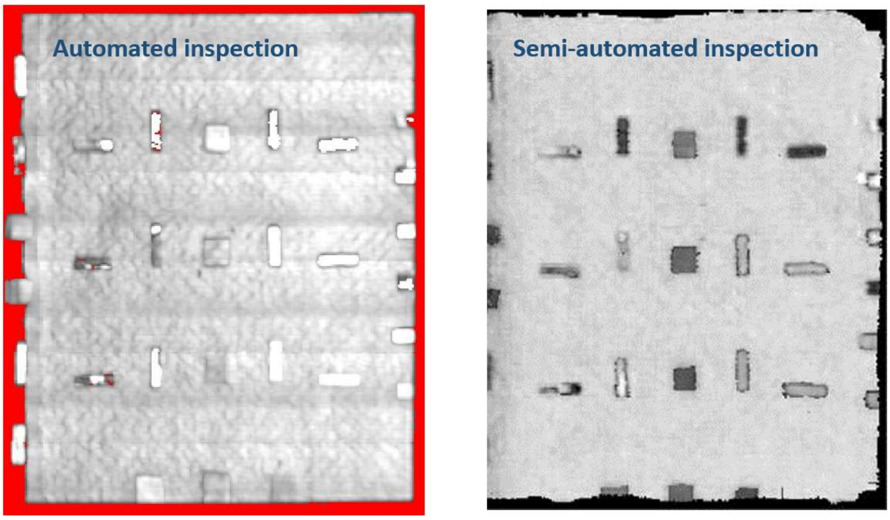

Figure 6. Comparative view of C-Scan records with amplitude signal. Left: data acquired with automated inspection system (water tank). Right: data acquired with semi-automated inspection system (Pulse-echo technique, 3.5 MHz)

Depending on the flexibility of the part, the rigidity of the holding fixture, and the UT technique, amplitude records may reveal slight variations due to the changes in pressure applied by the inspector. These changes are usually below 1dB, well within the tolerances for aerospace standards.

It is important to note that all the defects have near perfect resolution and there is no hysteresis observed even at speeds of 500 mm/s.

FASTER, BETTER, CHEAPER

Manual and semi-automated inspection systems are usually associated with low productivity when compared to automated solutions and typically relegated to the inspection of small parts. One of the main advantages of combining visual tracking with manual PAUT techniques is the ability to inspect very large parts with complete reliability and at fast inspection speeds. A CAMUS 3D inspection cell can accommodate parts that are up to 30m long, and have several inspectors scanning the part at the same time.

The inspection process is similar to painting with a broad brush. The monitor provides immediate feedback of the location of the brush and the results of the “painting” on the part. The real-time scan delivers instantaneous information on the quality of the results, and whether an area has been properly covered. This feedback permits operators to retrace their steps, increase or reduce the speed, or change angle and pressure depending on shape and geometry, surface conditions, and other inspection variables. The CAMUS 3D system has been measured to provide an average inspection speed on flat areas of approx. 200 mm/s, with productivity of 20 m^2/h. These values are typically in between those achieved with conventional semi-automated and fully automated solutions.

Another very important factor contributing to the high productivity of this equipment is new-part setup and part-change times. By eliminating robot programming, new parts can be configured in a matter of hours, while parts can be moved in and out of the fixture and be ready to inspect in minutes. Also, based on practical experience, CAMUS 3D has a clear advantage over fully automated systems when inspecting large and less-rigid parts where slight variations in shape during manufacturing, or flexing of the part when on the fixture can cause position variations that robots cannot handle, but a human inspector can easily accommodate.

From a cost point of view, a full CAMUS 3D inspection cell will typically cost 60-80% less than an equivalent robotic line and it requires considerably less space, maintenance, and safety considerations. This equipment can be delivered in 2-3 months and installed in a couple of days compared to the standard 12 months required for a fully automated line.

CONCLUSIONS

This paper shows how IR visual tracking technology has been integrated with a high-end PAUT instrument and software to provide wireless 3D encoding during manual inspections. Depending on the part and production volumes, this semi-automated tool can provide equivalent or better quality and productivity than a fully automated solution at a fraction of the cost. This encoding technique can also be used to upgrade a conventional UT inspection cell to PAUT without having to manipulate or reprogram the inspection robots or gantries.

Future work includes adding other scanners and techniques (e.g. EMAT), and improving the man-machine interaction using augmented reality and similar techniques.

REFERENCES & ACKNOWLEDGMENTS

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