Wireless 3D localization applied to the manual ultrasonic inspection of complex-geometry composite components

Fernando Ojeda
Tecnatom S.A., Spain, fojeda@tecnatom.es

Abstract

An innovative method is described for obtaining high-quality and reliable ultrasonic C-Scan images during manual inspection. This method is based on visual tracking techniques and allows for inspection of components with complex geometry, avoiding the need for electro-mechanical devices, such as articulated arms or wire-encoders. Additionally, the most critical requirements for this method are described and compared with traditional inspection methods, in terms of productivity, ease of operation, performance and cost. This analysis is based on the operating experience and results obtained in aeronautical production environments.

1. Introduction

Recent technologies grouped under the term “Industry 4.0” are accelerating and multiplying the possibilities of automation in many productive processes. This trend also involves the quality control processes based on Non-destructive Testing (NDT).

However, automated NDT inspections are not always technically and/or economically feasible. This is the reason why automated and manual inspection methods are still seen, and will be, working together. Even though the use of manual inspections is more evident in the MRO phase (Maintenance, Repair, Overhaul), they are also found in the most advanced factories within their productive processes.

Ultrasonic techniques (UT) are widely used for such manual inspections in the aeronautical sector to verify integrity of several materials. As in every manual process, UT manual inspections are tightly coupled to human factors. This is very relevant due to the lack of a spatial record (C-Scan) that guarantees coverage and quality of the inspection (e.g., coupling and correct position of the probes respecting the part under inspection).

Currently, there are several solutions to obtain a C-scan record in manual inspections, as an intermediate step between manual and automatic inspection. These are the so-called semi-automated inspections, with much lower cost and complexity as compared to an automated solution (e.g., robot-based).

Semi-automated inspections usually require of some device mechanically attached to the probe to determine its position in space: wire-encoders, encoded wheel membrane, metrological articulated arms, X-Y scanners, flexible linear guides, etc.
All these devices impose in some degree obstacles and mechanical limitations to the probe movements, reducing or hindering their degrees of freedom, which provokes UT coupling constrains, limited accuracies, etc. These limitations become even more serious when the geometry of the part is complex. Because of these limitations, these devices have a very restricted range of applications, and/or demand some degree of expertise and skill from the operator if a reliable C-Scan record is needed.

This paper introduces an innovative and alternative method to perform ultrasonic UT inspections, in a reliable and accurate fashion, with a low dependency on human factors. This method is based on three-dimensional (3D) spatial location of the probe through infrared (IR) vision. Since this method implies no mechanical coupling with the probe, inspection of components with complex geometry and big size is facilitated.

Presented experience and results come from the inspection in production environments of composite materials (CFRP, Carbon Fiber Reinforced Polymer), commonly used in the manufacturing of many structural aeronautical components nowadays.

2. Description of the Inspection System

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

![Block diagram of the UT inspection system based on infra-red visual tracking.](image)

The following core components conform the presented system:

1. **Data Acquisition System (DAS)**. A SONIA Phased-Array instrument, and InspectView software for acquisition and evaluation of UT data in a 3D environment.

2. **UT module**. This module comprises: (1) a linear Phased-Array ultrasound probe, usually of 32 or 64 elements, with flat or curved geometry, depending on the shape of the part (flat or radius, respectively), (2) wedge for mechanical contact to the part surface, (3) bubbler for ultrasonic coupling in local immersion, (4) device for ergonomic handling of the assembly, and (5) IR markers for the spatial location of the module (small spheres reflecting light in the infra-red spectrum).


3. **Infra-red vision system.** This system contains several infra-red cameras (from 3 to 20), depending on the size of the part being inspected. These cameras are conveniently placed to locate the inspection module and assure it is correctly tracked by at least three cameras anytime. This is required by the spatial triangulation algorithms, which are processed in real-time by a central processing unit (CPU), producing as an output the 3D coordinates of the UT module. These coordinates are continuously transferred to the DAS.

4. **Water system.** The bubbler holding the transducer is continuously supplied by a small water flow to achieve a correct ultrasonic coupling. A tray collects the wasted water and a water pump brings the water flow back to the probe.

5. **Supporting fixtures.** This is essential to obtain the required mechanical stability of the part during the inspection process. The supporting tool has IR markers for a correct location of the part relative to the inspection module.

Inspection technique is always Phased-Array UT Pulse-Echo (PAUT-PE), adapting the geometry of the transducer and wedges to the wide range of geometries that can be found in production parts (inner/outer radius, ramp, basins, etc.). If it is necessary, different frequencies can be used (typically 3.5 or 5 MHz).

Figure 2 shows an example of industrial implementation of the described system for the inspection of aeronautical components in factory. Commercial name for this system is WiiPA. In this configuration, the system has eight IR cameras installed on the top of a metallic structure, surrounding the perimeter of the inspection area, and assuring the visibility of the UT module by at least three cameras simultaneously.

![Image of the system](image)

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

Additionally, this structure is used for the wiring and piping of the UT module, water circuit and several monitors to show the output of the acquisition software.
3. Critical requirements

This section analyses the most critical requirements in the application of infra-red vision systems for implementing a semi-automated UT solution in a productive environment. The main aspect to be considered is the generation of a reliable C-Scan record.

1. **Ultrasonic coupling.** There are several coupling methods to perform PAUT-PE inspections, either manual or semi-automated inspections. These include “dry coupling” with flexible polymer membranes. The most reliable and productive method is the one used by the automated systems: continuous supply of water into a probe bubbler to keep local immersion. This involves a closed-loop water system for pumping, filtering and collecting water.

2. **Ergonomics.** Ergonomic requirements are critical in a productive process where persons and therefore manual effort are involved. In all cases, these efforts must be reduced, and comfortable and safe operation conditions must be ensured. These requirements must be considered in the design phase of each system, considering aspects such as the height of the fixture, position of the monitors, design of the UT module, support for the wires, etc. As an example, figure 3 shows an implementation example of the IR markers on the UT module to favour an ergonomic operation.

![Figure 3. Detail of ergonomic implementation of the IR markers on the UT module.](image)

3. **Latency control.** One of the issues of the IR tracking systems to deal with, when compared to more traditional devices such as wire-encoders, is the processing time for the spatial coordinates and their transference to the DAS. This time can be in the range of units or tens of milliseconds. Even though manual inspection speeds are not very high (less than 150 mm/sec), these delays can easily produce “hysteresis” effects in the C-Scan records, and therefore, image distortion. This can become worse if the inspection speed goes higher and may seriously limit the detection capability of the system as well as defect resolution. To avoid this effect, latency must be reduced or eliminated with a proper integration of the IR vision system and the SAD.
4. **Resolution, accuracy and repeatability.** UT inspection of parts with complex geometry requires high resolution, accuracy and repeatability, normally between 0.1 mm and 1 mm. Most of these requirements are related to the IR vision system, but they also involve a good mechanical characterization of the part and the UT probe, as well as a reliable supporting tool. Additionally, accurate and fast calibration and three-point correction tools are needed. This is essential for a quick set-up after small movements of the part, cameras, or even the own supporting tool.

5. **Lighting and shiny elements.** IR tracking systems can be affected by the presence of interferences of infrared light from unexpected reflectors of intense light sources, either natural or artificial, provoking location errors. To avoid these errors, IR markers follow a geometrical pattern easily recognizable by the vision system, being in this way quite immune to the presence of unexpected sources of light. However, it is recommendable to take this aspect into account during the design of the inspection cell, trying to keep this sort of shiny elements out of the vision field of the IR cameras (outdoor windows, mirrors, metallic elements, lamps, etc.).

6. **Human-machine interaction.** Design of the man-machine interaction (“Human-Machine interface”) is a critical aspect in manual operations, especially in terms of safety, reliability and productivity. In solutions like the one described here, software interfaces must be optimized to help during the inspection process. Among other things, the evolution of the C-Scan must be shown on real-time, as well as the position of the inspection module. Along the same line, the system must contain hardware devices that help the operator to pause and resume the process during the inspection, keeping the data already acquired, and software tools to re-test doubtful areas of the C-Scan during acquisition process.

7. **3D environment.** In the described application, it is imperative that software for acquisition and analysis can compute UT and position data in a 3D environment, considering the real geometry (or a very approximate one) and position of the part and the inspection module at any time during the whole inspection. In addition, software tools must be available for developing 3D images in a 2D world, needed for UT analysis, even when geometries are not analytically developable in that world, and keeping all the time 3D information for a correct defect sizing and ultrasonic analysis. Figure 4 shows one of the mentioned tools, focused on 3D geometry adaptation.
8. **Combined records.** In the aeronautical sector, you can usually find parts with different areas, and each of them must be inspected with a different approach. Total or partial changes may be needed in the UT module (probe, shoe, etc.) during inspection. A typical example is found in the inspection of parts combining flat surfaces and radii (either inner or outer). In these cases, it is important that all the inspected areas are integrated in a single C-Scan. This simplifies UT evaluation, which is the next step.

4. **Results**

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

Figure 5. Comparative view of C-Scan records, both in amplitude and sound path. Obtained with the WiiPA 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, rigidity of the holding fixture, and the UT technique, amplitude records may reveal slight variations due to the unavoidable changes in strength applied by the inspector on the part and resulting position. These changes are usually below 1 dB and are assumed by the current aeronautical regulations.

Finally, all the defects are located with correct resolution. No hysteresis effects are observed, even with speeds up to 500 mm/s.

5. Operating experience

Manual and semi-automated inspection systems are usually associated with a low productivity when compared to automated solutions. Therefore, they are mostly applied to small-sized parts.

One of the advantages of the system described in this paper, combining visual tracking with PAUT techniques, is the ability to inspect large-sized parts in a reliable and therefore productive fashion.

Process can be compared to a brush painting, where HMI helps the inspector to reduce overlapping areas, and corresponding waste in inspection time. In the same line, the features of the system help to achieve a reliable ultrasonic coupling. This lets the inspector have enough freedom of movement over the part, allowing for higher inspection speeds without compromising the reliability of the C-Scan record.

Obviously, all these aspects depend on the part and UT technique employed. On flat-like areas, average speed can be around 200 mm/s, with effective productivity of 20 m²/h. These values are between those achieved with conventional semi-automated and fully automated solutions. Cost also lies between both options, but much closer to that of a manual inspection.
Additionally, camera system allows for coverage of very large areas, up to 30 m long. Moreover, a single vision system may be shared among multiple DAS simultaneously. This may be applied for the inspection of a big part shared by several inspectors at the same time, or to scan multiple parts in a single inspection cell in parallel. Obviously, all these features provide a clear benefit in terms of productivity and optimization of the available space in factory.

Other aspect linked to productivity is the easy and agile change of parts, either when they have the same geometry or when a new geometry comes into the system. Our experience with this system shows a clear advantage in this point, when it is compared with automated systems usually available in the aeronautical sector. The latter are very demanding about part positioning, and even more when parts are flexible or the manufacturing process allows for slight variations between parts of the same model. In this line, the manual approach of the presented manual solution lowers these requirements, reducing enormously times for part change and inspection set-up.

6. Conclusions

This paper shows how IR visual tracking technologies can be applied to improve the PA-UT manual inspection process, providing significant advantages in terms of productivity and reliability, at a much lower cost than that of an equivalent fully automated solution (able to inspect parts with arbitrary complex geometry and data analysis in a 3D environment).

Looking ahead, it seems reasonable to expect this system to benefit from other technologies, especially those focusing on man-machine interaction (e.g., augmented reality, which is currently being developed by Tecnatom for 3D holographic projection of C-Scans on the part under inspection), and to be applied on other industrial sectors, beyond aeronautical production.

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