Automatic methods for ultrasonic scanning paths generation

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Abstract

This paper presents the last evolutions of a program developed in 2020 for the automated generation of optimal scanning paths for 0°LW ultrasonic inspections of complex parts. After summarizing the overall concepts of the path generation method, the paper presents two new algorithms (*side following path* and *side/radius interpolating path*) recently developed for specific geometries such as long and thin parts, or parts including nonparallel radii. Trajectories automatically generated by the software are then presented for a collection of various aerospace and industrial CFRP components. The results show that the software was able to generate optimal paths for all the tested geometries, using the part's 3D surface CAD and the probe's characteristics as only inputs. In particular, the addition of the new algorithms allows for the generation of satisfactory trajectories even for the parts that were previously problematic.

KEYWORDS: Ultrasonic scan plans, Automation, Off-line programming

1. Introduction

The ultrasonic inspections of CFRP components by automated equipment such as gantries, immersion tanks or robots require accurate scanning plans. Generating optimal inspection paths for complex components is not trivial. Some generic path planning tools are commercially available and can be used or adapted, but few or none are specifically designed for non destructive testing purposes. These tools usually do not consider specific aspects of ultrasonic inspection (UT), such as ensuring the coverage of the part by the ultrasonic beam or maintaining the orientation of a phased-array probe during the scan [1]. Our aim was to develop fully automated methods of path generation dedicated to 0°LW pulse-echo UT inspections that would work on a large variety of geometries with minimal human intervention. The generated scan plans should fully cover the inspected component while using the smallest number of passes and generate the classical 2D ultrasonic images (C-scans). In our earlier work, we developed different algorithms combining a variety of existing mathematical tools to solve these challenges [1]. The main concept is to compute the trajectory directly from the part's geometry instead of relying on technicians' experience. These algorithms gave good results on a variety of components, but also demonstrated some limitations for specific, but still frequent components' geometries. This paper briefly recalls the main steps of our generation tool, then details two new algorithms specifically developed to overcome the issues encountered with some geometries, and finally presents and discusses the results obtained by its application on a variety of industrial and aerospace components.

2. Overview of the method

This section presents a quick review of the required offline preprocessing and path planning steps. Details about each step can be found in [1]. The section ends with a description of some limitations of the previous path generation algorithms.

2.1 Preprocessing

The developed process is based on a 3D surface model of the part. For some parts, restrictions imposed by the mechanical system may require the initial surface to be broken down into smaller surfaces. The surface is converted into a triangle mesh to help compute a 2D representation of the part, which is necessary for most path generation methods and interoperability with the UT instrument. The triangle mesh also allows easy computation of curvature, normal vectors and other geometric quantities that are used to generate paths and estimate coverage. The next step is to construct a mapping of the 3D mesh to the 2D plane using a method called *Boundary First Flattening* [2]. It computes a flattening that minimizes area distortion and preserves the general shapes of the part. This mapping can be inverted to transform coordinates from 2D to 3D. The ability to transform between 2D and 3D representations is necessary because the most common UT analysis software usually operate in 2D while scanning systems (either a robot or a cartesian system) move in 3D. Figure 1 shows a CAD model, its mesh representation, and the flattened mesh.

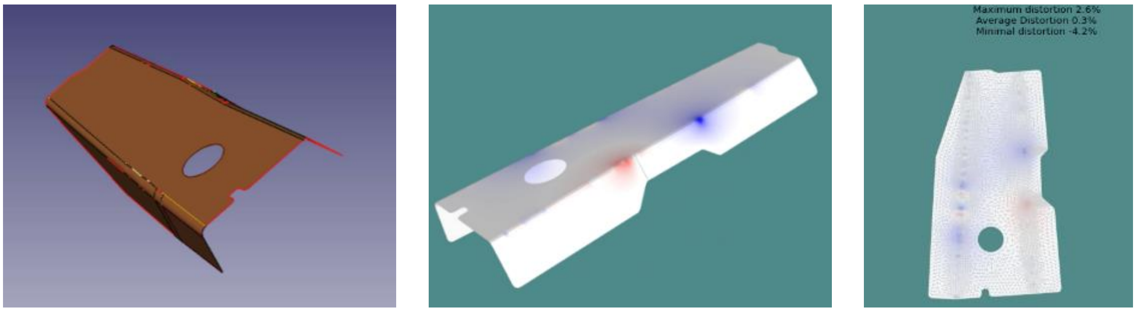

Figure 1. Left – Example of 3D surface CAD; Center – Meshed surface; Right – Flattened mesh with colors representing the area distortion caused by the flattening.

2.2 Path generation

The large variety of industrial parts' shapes makes it nearly impossible to use a single algorithm for path generation. Hence, four different algorithms were developed prior to this work. All these algorithms use a simple model to estimate the ultrasound beam and to ensure a complete coverage of the part. The first method is a *raster scan* constructed on the 2D mesh. The distance between scan lines can be fixed or automatically adjusted according to curvature in the index direction: greater curvature leading to scan lines that are closer. This method is usually used on simple parts such as plates. The second and third methods are similar because they both use principal directions to compute *minimum curvature paths*. One works on 3D mesh and the other one on 2D mesh. Both methods produce scan lines that curve along the surface. They are used on shapes such as L and U surfaces. The last method generates an initial scan line using the principal direction of least curvature on the 2D mesh. This line is then swept across the part, producing parallel lines (in 2D). This is called the *minimum curvature sweep* method. It was developed specifically for long parts such as spars or stringers, but it also gives good results on a wide variety of shapes such as Z shape parts.

2.3 Simulation and offline programming

Scan plans are then automatically transferred to a robotic simulation program for visualization in their real environment. This allows verification of the scanning plan in the inspection cells to prevent robot singularities, to verify that the robot's reach is sufficient, and to avoid collisions. Once satisfied, the program is exported to a specific robot or PLC format for inspection.

2.4 Limitations of the path generation algorithms

While the four path generation methods were able to adequately process a large variety of parts, two main classes of geometries remained challenging: parts that are much longer than they are wide (typically aerospace stiffeners or stringers), and parts that have two or more nonparallel radii. Two new path generation algorithms were developed specifically for these types of geometries: the *side following path* and the *side/radius interpolating path*. The latter proved to also give excellent results for most other types of geometries as well. These two new methods are presented in the next section.

3. New path generation algorithms

This section describes two new algorithms developed to address issues in path generation for long and thin parts and for components with nonparallel radii. Both methods use the flattened 2D mesh. Results using these methods are presented in the next section.

3.1 Side following path

This method starts by finding the longest side of the part. A side is defined as a connected section of the part boundary in which the tangent vectors are approximately parallel. In practice, this is done by first identifying the outside boundary of the part: an ordered sequence of edges of the mesh. These edges are clustered into sides using agglomerative clustering with Ward linkage [3]. This algorithm gradually builds up the side by assigning edges to sides to make edges in each side similar in direction while making sides as dissimilar as possible. Once sides have been found, the longest one is easily extracted. This side is then swept across the part using the same curvature-based rule as in the previous methods to compute distance between scan lines. This method produces parallel scan lines which are also parallel to the longest side of the part. It performs well on parts with relatively simple boundary shape and produces good scan plans on long and narrow parts.

3.2 Side/radius interpolating path

This method is an extension to the previous method that can process more complex parts. It starts by segmenting the mesh faces based on principal curvatures using, again, agglomerative clustering. The segments correspond to regions of the part that have similar curvatures. It extracts flat regions as well as regions corresponding to radii. For each of these regions, the two longest sides are computed using the same algorithm as in the side following path method. These are usually two opposite sides of each segment. For segments that are radii, a third "side" is defined, halfway between to the two opposite sides, by linear interpolation. Then, for each segment, scan lines are added by interpolating between successive sides. This method works well on various geometries, including long narrow parts and parts with nonparallel radii.

3.3 Additional smoothing step using splines

An optional step to the former methods is to use spline interpolation between points. This allows for manual manipulation of scan lines and points directly on the 3D meshes, which is particularly useful for complex components with numerous curvatures, or parts with significant differences between the CAD and the actual curvature, such as castings.

4. Results

This section presents scan plans obtained using the various algorithms and highlights their performance and limitations. The raster scan method works well on parts with small curvatures and when the longest direction is parallel to the desired scan direction. For such parts, a raster scan with constant indexing produces a satisfactory plan. **Error! Reference source not found.** shows a scan plan obtained by the raster scan method on a large aerospace part.

Parts with a single significant radius can also be processed using the adaptive indexation to obtain good coverage near the radius (see the two rightmost panes of Figure 2). The same method, however, fails to generate good plans on more complex geometries. The halfpipe presented in Figure 3 has significant curvatures in two different directions and the plan should scan along the pipe which is impossible to do with straight lines in the 2D representation. The raster plan shown on the left of Figure 3 is inefficient due to the high number of scan lines where there is no part present. For such parts, the minimum

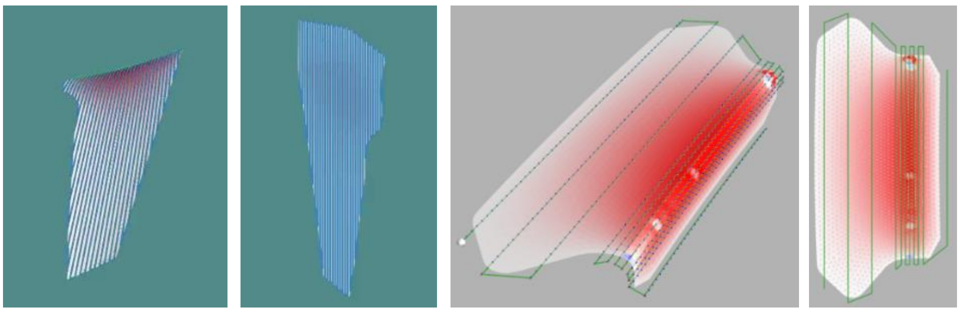

Figure 2. Raster plan with constant spacing between scan lines for a large aerospace part (leftmost two panes). Raster scan with automatically adjusted spacing between scan lines for a part with a single radius (rightmost two panes).

curvature methods give better results. The scan plan follows the part geometry much more closely with scan lines that curve along the direction of the part. The central pane of Figure 3 shows the minimum curvature plan obtained on the halfpipe.

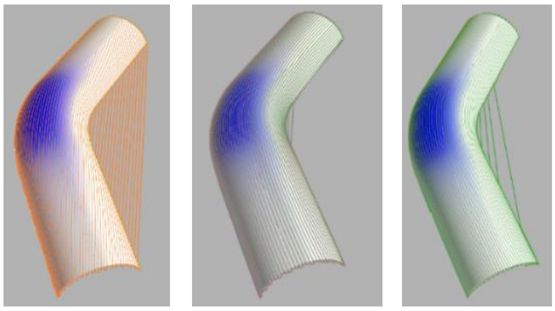

Figure 3. Halfpipe with significant curvature in two directions. The raster scan plan does not follow the part geometry (left) while a minimum curvature plan produces scan lines which move along the pipe, from one end to the other (center). The minimum curvature sweep produces equally spaced scan lines (right).

Figure 4 shows a minimum curvature path on a part with two nonparallel radii. Because the minimum curvature directions are computed by trying to minimize direction changes, the path does not follow both radii directly. While these methods work well, they are more unstable and obtaining a good path sometimes requires tweaking many parameters. Another limitation of these methods is that nothing forces scan lines to be parallel. This sometimes leads to inconsistent spacing between scan lines, especially on large parts.

The minimum curvature sweep is often easier to use while still giving good scan plans. The right pane of Figure 3 shows a plan obtained using the sweep method. This method ensures the scan lines are parallel in 2D which translates to nearly parallel scan lines in 3D if the flattening did not produce large distortions.

The sweep method has limitation for parts with two nonparallel radii. The first two panes from the left in Figure 5 show the sweep method on a part with two parallel radii and on a part with two nonparallel radii.

The side/radius interpolation method leads to much better results for parts with two nonparallel radii and for long and narrow parts. The right pane of Figure 5 shows how the method is able to generate a good scan plan on a part with two nonparallel radii.

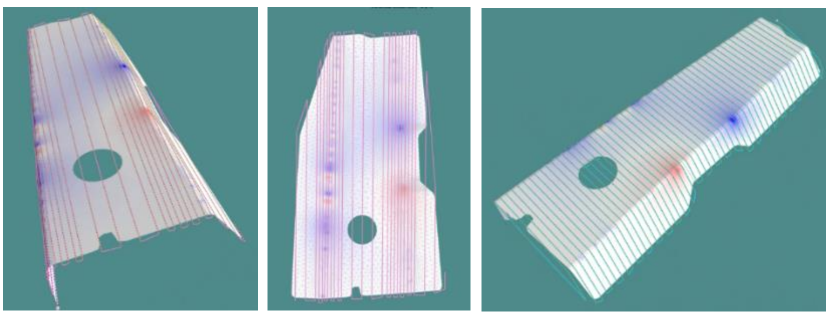

Figure 4. Minimum curvature paths on the 3D surface (left) and 2D representation (center). The right pane shows it is possible to swap the scan and index directions.

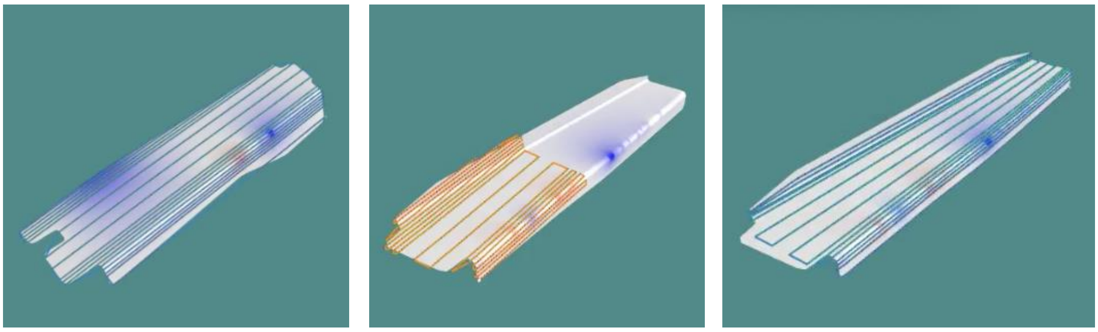

Figure 5. The minimum curvature sweep method gives good results on a part with parallel radii (left) but fails to generate a satisfactory path on a part with nonparallel radii (center). The side/radius interpolating method generates a good path on the part with nonparallel radii (right).

5. Conclusions

A complete software solution was developed for the path programing of 0°LW pulse-echo ultrasonic inspections. This off-line solution allows for automating most of the tasks that would usually require an experienced NDT inspector. Using a 3D surface CAD and the probe's characteristics as only inputs, the software generates trajectories adapted to complex geometries in a few seconds, while ensuring an optimal ultrasonic coverage of the part. A post-processor allows to output the generated path into commercial robotic software. Our software includes different generation algorithms whose performance can vary depending on the part's geometries. Two new algorithms (*side following path* and *side/radius interpolating path*) were recently developed to overcome problems encountered with the former algorithms in the case of long and thin parts, and for parts including nonparallel radii. During an extensive test period, the software was used on a collection of various aerospace and industrial CFRP components. With the addition of the new algorithms, the tool was always able to generate satisfactory paths even for parts that were previously problematic.

Acknowledgements

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