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Procedia Engineering 63 (2013) 779 – 785

Procedia Engineering

www.elsevier.com/locate/procedia

The Manufacturing Engineering Society International Conference, MESIC 2013

Visualization software for CT: fan/cone beam and metrology applications

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Abstract

This paper presents the high-performance capabilities developed in specific software for industrial computed tomography (CT) applications. The Technology Center AIMEN has developed in the last years a computed tomography system, in collaboration with the USC, for non-destructive testing and metrology purposes. A visualization tool was implemented for the CT system including 3D rendering and image reconstruction, following the continuous evolution of the system. Image reconstruction accounted for the system's initial fan beam geometry, based on filtered backprojection algorithm. Further development of the CT system with a flat panel detector needed a reconstruction tool for cone beam geometry.

Final version of the visualization software accomplishes specialized visualization and applications: reconstruction for different geometries, higher computer memory requirements and CAD and metrology applications in industrial x-ray imaging. This tool has resulted in flexible software with the highest capabilities and further possibilities, adapted to the emerging needs of industrial CT.

Keywords: computed tomography; metrology; visualization; 3D reconstruction

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1877-7058 © 2013 The Authors. Published by Elsevier Ltd.
Selection and peer-review under responsibility of Universidad de Zaragoza, Dpto Ing Diseño y Fabricacion
doi:10.1016/j.proeng.2013.08.266

1. Introduction

Industrial X-ray computed tomography (CT) is a method whose relevance has increased more and more because of its great advantages. Its versatility for Non-Destructive Testing (NDT) applications covers different areas of interest, as it allows the 2D and 3D measurement of components in order to find hidden characteristics or errors (e.g. shrink-hole, cracks, inclusions, pores, etc). Moreover, it is possible to determine physical variables like porosity and density. Industrial fields as petrochemical, composites structures, aeronautics, precision castings and forgings, engineering ceramics and powder metallurgy and assembled structures (ranging from automotive, energy...) are currently employing CT inspection for quality control of those special and/or expensive parts, along with analysis solution of production errors.

Furthermore, one of the most promising CT industrial applications is dimensional metrology, which, along with quality control in production, enforces the high requirements for processing software on acquired CT images.

The Technological Center Aimen is oriented to welding technology and different industrial research areas. Different pieces (in terms of size and density) must be analyzed in its NDT facilities, so a customized CT system for both tomography and digital radiography applications was developed in collaboration with the University of Santiago de Compostela (USC), Franco et al. (2010), (2011). The CT system was based on a dual X-ray source (focal size of 0.4/1 mm) up to 225 kV maximum energy and a linear scintillator array of 1 meter length. Acquisition of images covers pieces up to 900 mm height, 800 mm diameter and 40 mm maximum width for steel. Spatial resolution up to 0.5 mm and better is achieved (depending on the piece to inspect), for both radiography and tomography images.

Recent hardware actualization of the CT system has consisted on the integration of a flat panel detector (XRD 0822 AP14 from Perkin Elmer). The aim of this implementation is to obtain better resolutions, up to 50 - 100 μm, although limited for small pieces (or small areas within larger parts). With this implementation, applications as dimensional measurements can be solved, increasing the previous precision. Due to this, additional software capabilities are required, since the CT geometry changes to a cone-beam exposure along with dimensional tools.

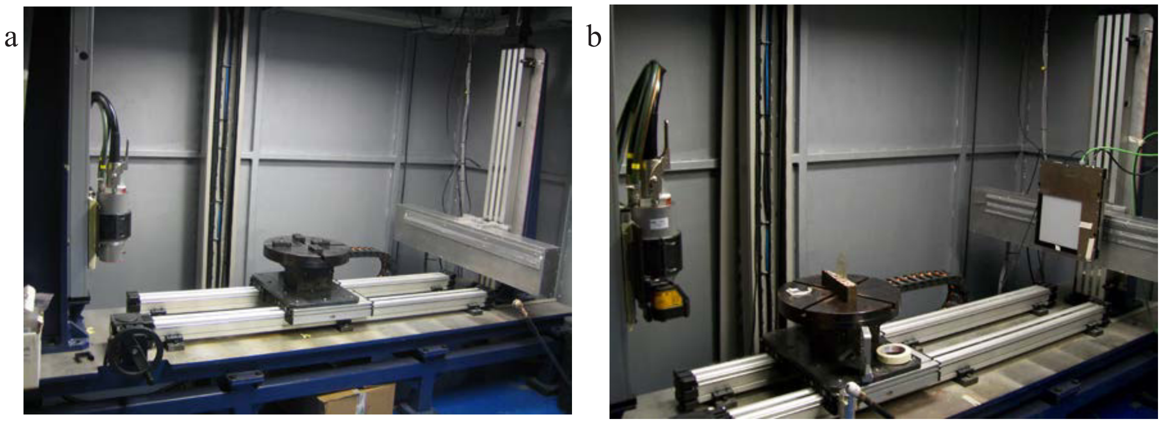

Fig. 1. (a) CT system in AIMEN, linear detector; (b) flat panel implementation.

1.1. Computed tomography

Computed tomography is a NDT radiographic method, based on the x-ray transmission through the piece to inspect. X-ray radiation crosses the piece and reaches the detector, generating a signal representing the initial intensity of the source modulated by the piece's absorption (depending on the density, atomic number and width of the piece). The object to inspect is situated between the source and the detector, and a complete rotation is performed (360º) for measuring.

Logarithm of the ratio between the attenuated and non attenuated signal represents the line integral (Radon transform) of the linear attenuation coefficients within the material, and it is defined as a projection for each angular position. Projections for different incident angles are acquired for 360º and the final data matrix is called a sinogram. Final CT reconstructed image is obtained from the sinogram.

CT geometries (fan and cone beam) considered for the Aimen CT belong to the 3rd generation CT systems, where the piece is irradiated completely during rotation. The fan beam geometry defines an arc beam for the irradiation, so a slice of the piece to inspect is irradiated and acquired in a complete rotation, by collimating both the source and the detector. In cone beam geometry, no collimation for beam generation is needed and the piece is irradiated covering the 2D detector surface (as the flat panel) during the rotation.

The reconstruction algorithm for fan beam is the well-known filtered back-projection algorithm, based on the Fourier slices theorem. Reconstruction algorithm for 2D detectors (cone beam CT) is based on the Feldkamp-David-Kress algorithm, Feldkamp et al. (1984), by rewriting the Radon transform for two dimensions.

1.2. Image format

Available image formats in the CT system include general purpose ones like TIFF, Analyze SPM or DICOM/DICONDE (in NDT) and customized formats specially designed for acquisition data. Thus, initial images for CT (radiographies and sinograms) are raw data files with an included header of parameters (with general and geometrical information from the acquisition). Digital images are directly visualized in 2D and 3D views, depending on its proper characteristics (volumetric or not), since the software allows the reconstruction of tomography slices before its visualization. Reconstructed tomography format is Analyze SPM, www.mayo.edu, a known format which organizes CT images in 2 sets: one separated header file (*.hdr*) and an image file (*.img*) with the reconstructed data.

It is possible to export tomography images to STL format within the software application for visualization. STL is a file format native to CAD software and it consists on a raw unstructured triangulated surface, given by the unit normal and vertices of the triangles. It is widely used for rapid prototyping and computer-aided manufacturing, so its interest from CT images is straightforward in engineering applications.

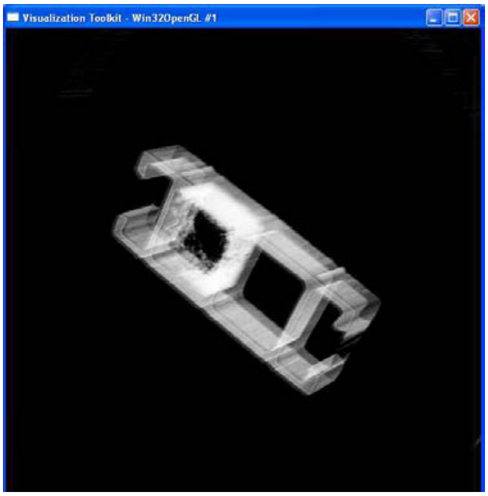

Fig. 2. Example of 3D rendering of an Al structure with plastic foam insert

Consecutive work and development for applications in measuring and NDT has led to the CT system updating and further needs. For example, memory usage: it largely increases for higher resolutions and larger pieces, along with 3D applications. CAD and metrology applications are also involved in the developed software, as it will be explained in the following sections.

Final version of the visualization software has evolved as a flexible tool for all the working requirements from an industrial CT. The system is configured as an open tool that allows the development of new plug-ins, facilitating the ability to create new applications as a result of the successful collaboration between the two institutions.

2. Methodology

The computer program has been written in C++ as a multiplatform graphic tool. Qt, Nokia corporation, and VTK, Kitware Inc, libraries were used for developing the user interface and 3D rendering, respectively. The software unifies both the reconstruction and the visualization of tomography and radiography images in a unique tool. Other processing capabilities include characteristics extraction and image manipulation (window-level, zoom, pseudo-color), image filtering and basic feature extraction: position and gray values information, profile plots, histograms (see Fig. 3).

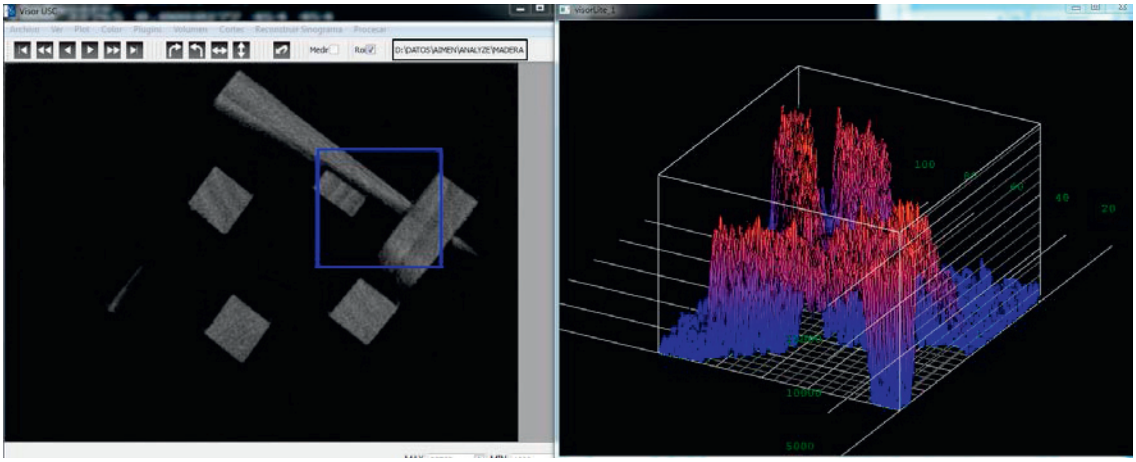

Fig. 3. Example of sectional feature extraction and 2D profile plot

Moreover, the functionality of the software includes 3D visualization, STL format and the reconstruction for the new cone-beam geometry:

2.1. 3D empowered visualization

Computed tomography (CT) and digital radiography (DR) images, when working in industrial environment, imply large-sized image files. Radiographs and sinograms must be imaged along with CT series for 3D reconstruction (in Analyze SPM format).

Different capabilities have been implemented for the high memory needs. For example, whole or sectional areas (within the slices or specific slices) can be chosen for reconstruction. 3D rendering allows two possibilities: one based on the use of an opacity function and the second based on an isosurface of the volume. Both volumetric representations allow navigating inside the image in order to inspect and detect any possible flaw or characteristic of the material.

- 3D rendering

Opacity rendering defines an opacity function from the data volume histogram to define the appearance of the 3D image. This function allows enhancing different densities of the materials in the same object. To visualize the inner structures of the volume, background or noise pixel values are mapped to 0.0 opacity and they do not contribute to the final rendered image.

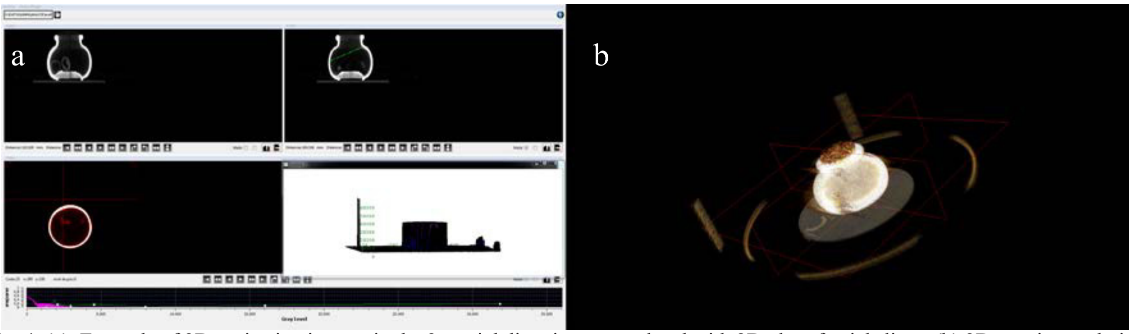

Fig. 4. (a) Example of 3D projection images in the 3 spatial directions, completed with 2D plot of axial slices; (b) 3D opacity rendering

For the piece's contour rendering, isosurfaces have to be calculated previously in order to approximate the contours. The Marching Cubes algorithm, Lorensen and Cline (1987), is used to built the 3D surface, which considers, for representing the isosurface at each point in the image, a cube formed by the 8 neighbour locations to determine the polygons representing the isosurface. The individual obtained polygons are then fused into the whole desired surface. Pre-calculated values of the 256 possible polygon configurations are employed to accelerate the computation process.

- Image filtering

On the other side, image filtering in the visualization software also accounts for two possibilities. First, common filtering on images, with 4 known filters: smoothing, Wiener, median and Gauss filtering, in order to highlight details or to eliminate image artifacts. Moreover, individual filtering has been implemented within tomography reconstruction to eliminate beam hardening artifacts in aluminium or steel pieces. This filtering corrects the attenuation values on the sinogram, based on a previous polynomial fit. Polynomial coefficients have been calculated for aluminium or steel materials by fitting real and theoretical attenuation measurements. An extra open filtering is considered for other materials whose polynomial coefficients can be further calculated, so this correction can be implemented directly without reprogramming the software.

3D empowered visualization allows the user to visualize the reconstructed images as their projections in the 3 spatial directions, as it can be seen on Fig. 4. This characteristic has been developed with the VTK library built in C++, an open-source, freely available software especially developed for 3D computer graphics, image processing and visualization. The software allows to obtain the 3D projections of the piece in different orientations (transversal and longitudinal), improving the user's inspection and visualization of the inside structures.

2.2. STL data format

The 3D reconstruction can be based, as indicated before, on the piece's surface. In this case, a STL file is generated from the CT image which can be used as an input file in CAD applications, so additional engineering models (polygonal, iges) can be generated from this STL basis for developing CAD work. The STL format uses a mesh of triangles on the surface to define the shape of the object. Therefore, it is necessary to apply isosurfaces rendering as a preliminary step in the generation of the triangles' mesh.

The STL file describes the raw unstructured triangulated surface by encoding the vertices of the triangles and the corresponding normal vectors. No representation of color or texture is added and for polygons with more than 3 vertices, only the first three vertices are written. Nevertheless, the developed software allows modifying the number of triangles in the mesh to meet the balance between image detail and file size.

STL format has become of crucial interest for reverse engineering or rapid prototyping from the tomography information of a piece. Other applications for the STL information are considered for volume segmentation and data archiving (not only on industrial applications but for example on cultural heritage and paleontological purposes, Keefer et al. (2006)).

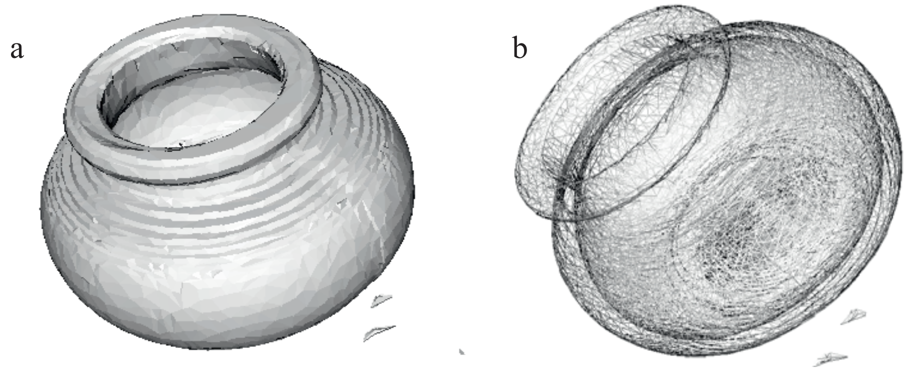

Fig. 5. (a) Example of 3D rendering on piece contour; (b) STL export file

2.3. Cone beam geometry

As it was explained before, CT reconstruction in this software was limited to a fan beam geometry solution. With the flat panel, i.e., 2D detector implementation for higher resolution and faster acquisition for small pieces or parts, a new reconstruction based on the cone beam geometry has been added to the visualization software, following the Feldkamp-David-Kress algorithm. New artifacts arise on reconstructed images, so the working filters above defined (single ones and beam hardening) are also implemented for the flat panel tomography images, along with the rest of the processing capabilities and data analysis.

Radiographies from the new detector differs from the previous ones (data format), leading to a global change on the header characteristics to manage the different formats in the CT system inspection capabilities (Fig. 6). In this way, the software and visualization capabilities are directly and easily transferred to the new geometry detector.

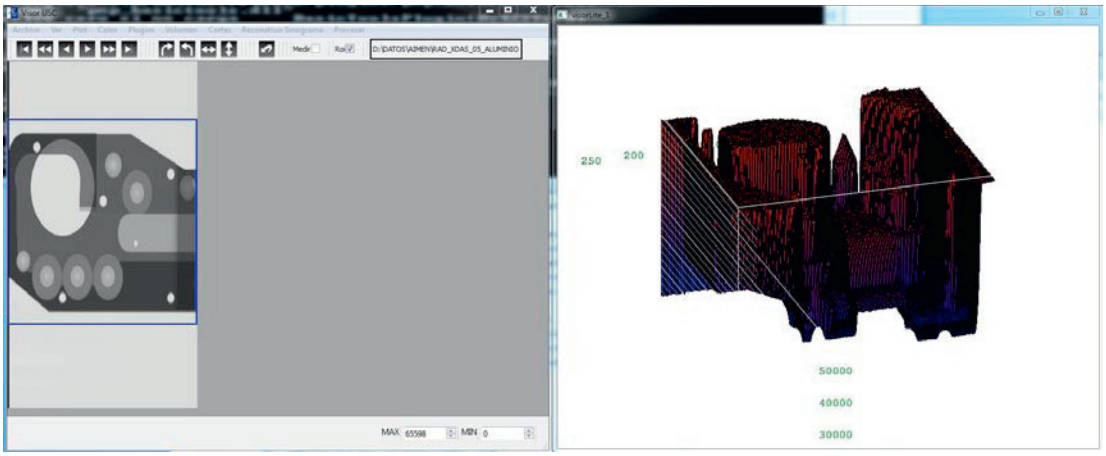

Fig. 6. Example of a projection view from the flat panel and 2D surface information

3. Results

This software deals with different image formats between radiography (for two digital detectors) and tomography (sinograms and reconstructed images). Tomography reconstruction is implemented for both fan beam and cone beam geometries. Extra capabilities include measuring tools (distance, profiles, region of interest's statistics) along with image filtering. Not only reconstruction-dedicated filtering has been implemented, but specific software filters for beam hardening are included, covering steel and aluminium parts and an open-material option.

The visualization tool has become a reliable software implement for working with digital radiography and tomography images in industrial applications. All the implemented tools help the inspector to analyze and perform NDT on industrial pieces, along with a visible output for part inspection for the manufacturer or engineer (STL, 3D images).

4. Conclusions

The CT and radiography oriented visualization software presented in this work is a powerful tool for industrial applications. Supported reconstruction for both fan and cone beam geometries, along with different 3D reconstruction, filtering and STL export, make it an improved and differenced software solution, with applications not only for the Aimen CT system but for other x-ray imaging based equipment. Applications on Non-Destructive Testing but on X-ray metrology and 3D CAD work can be easily implemented and utilized from this versatile tool.

Acknowledgements

This work was supported by Xunta de Galicia 10DPI007CT: Desenvolvemento dun sistema de microtomografía baseado en flat panel (TACIII). The presenting author wants to thank the collaboration of her colleagues at the NDT department.

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