Interior Surface Unwrapping System of Volume CT Data

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***Abstract*— Computed Tomography (CT) techniques are widely used in Non Destructive Examination (NDE) and Medical Imaging field for industrial inspection and medical diagnosis. While 3D rendering the CT data can be helpful in above mentioned applications, it is inefficient when extensive visual observation of a large number of internal irregularities of potential anomalies is required. This paper proposed a 2D interior surface unwrapping system based on unfolding methods in medical imaging field. A graphical user interface (GUI) is implemented to extract the CT skeleton structure for visualization and to allow efficient navigation of data and generation of 2D interior surface unwrapping representation. The program was tested with real world industrial volume CT data and generated satisfactory results.**

Keywords—Non-destructive Examination (NDE); Unwrapping; Volume Computed Tomography (CT); Software Tools for Imaging; Image-based Modeling and Algorithms;

I. Introduction

Non-destructive Examination (NDE) techniques are widely used in various industries for internal inspection of parts. Common methods include Visual Inspection, Magnetic Particle Inspection, Liquid Penetration Inspection, Ultrasonic Inspection, X-Ray Inspection, etc. The focus of this paper is on X-Ray Inspection, or specifically, Industrial Computed Tomography (ICT), which was used to capture the data used in this paper. It is capable of producing the three-dimensional representation of both internal and external of the scanned object and allow detection of flaw/defect to be performed. While off the shelf software programs like Autodesk 3Ds Max, Blender and Avizo are able to perform 3D rendering on the Volume CT (VCT) data, it is difficult for the inspector to manipulate the rendition when human expert inspection is needed. A 2D visualization method is therefore needed to present the data in a way that allow efficient manual visual inspection.

II. Problem Statement

A. Objective

Given the ICT volume data, design and implement a 2D visualization method to assist human inspector to detect internal anomalies such as defective drill holes and generate results that allow future development of automated detection.

This work was supported by GE Aviation.

B. Data Specifications

The VCT dataset used in this paper is the ICT scan of a generic turbine blade consists of 481 CT scans of size 733 by 1100 with pixel value represented by 16 bits. Metal pixels have high value of intensity (appear bright) while air pixels have low values (appear dark).

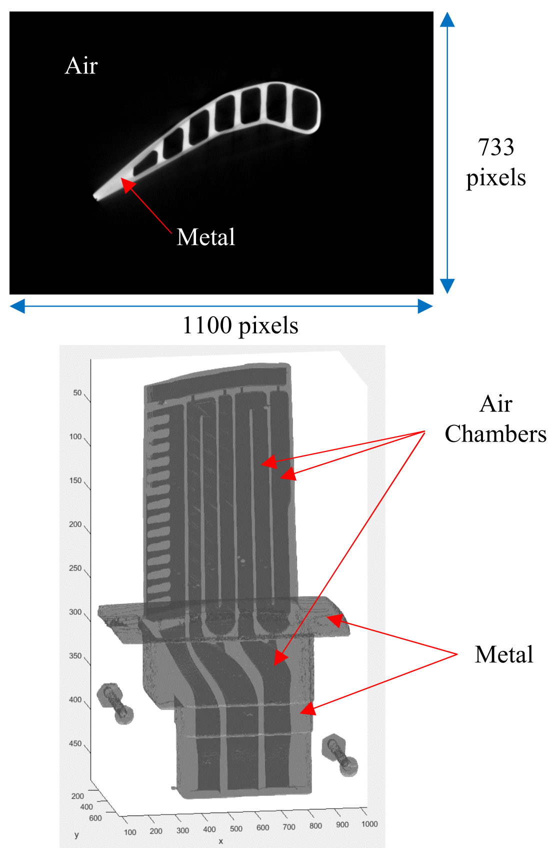


Fig. 1. Example of 1 CT Scan & 3D Transparent Rendering of the VCT Data

978-1-4673-9795-7/15 $31.00 © 2015 IEEE
DOI 10.1109/CSCI.2015.147

III. Literature Review

CT is one of the most widely used techniques in both industrial imaging and medical imaging field.

A. *Industrial CT*

Many different methods for data rendering of industrial CT data have been proposed. But they mainly focus on 3D rendering techniques such as volume rendering and surface rendering [1][2]. It is reasonable to reconstruct the volume data into three-dimensional model, but this model does not always allow effective detection of defect for the human inspector. For example, a defect on the internal surface of the component will require the expert to place a virtual camera inside the 3D model and pivot around to search for the defect. This can significantly increase the amount of time required to find any anomalies when the components to be observed is in large quantity.

B. *Medical Imaging*

While numerous research in the medical field also focused on the 3D rendering of the data [3], [4], in certain area, abdominal imaging specifically, a technique called 'unfolding/unraveling' is commonly used to turn the 3D model of human organ generated from magnetic resonance imaging (MRI) or CT into a 2D image with all the internal details preserved. This is usually done by reconstructing the CT source image data from the perspective of a virtual camera with the orientation perpendicular to the centerline/midline of the colon[5]–[8].

This method can be potentially applied to the data used in this paper. The process contains two steps: centerline extraction and data unfolding. For the former, various sophisticated thinning/skeletonization approaches have been proposed [9]. However, such approaches can be an overkill for the simple structure of air chamber as presented in the used data. It is possible to perform the extraction on 2D CT scans instead of the complete 3D data which may potentially introduce redundant computation complexity to the processing. For the unfolding part, a simpler algorithm can be developed since the medical unfolding approaches had to take physical properties such as elasticity of the organ tissue into consideration ([5], [6]) while such properties are not important in a metal industrial component.

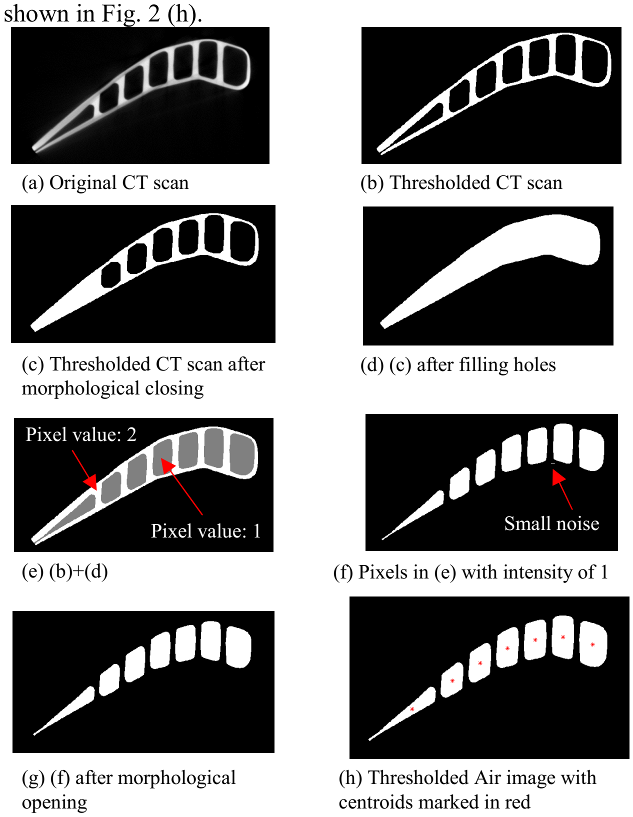
IV. Proposed Method

The main idea of the proposed method is to first find centerlines/skeleton in the air chambers. Then after a point of interest is selected by the user, adjacent points on the skeleton are used as origin points to perform polar coordinate transform on each of the CT scans. This would generate an 'unfolded' view of the turbine blade data from the selected air chamber. By flattening this unfolded data, an 'unwrapping' sequence of images can be generated from the flattened result to help the inspector identify anomalies in the blade.

A. *Skeletonization*

The process of extracting centerlines from air chambers in the turbine blade volume CT data is called skeletonization.

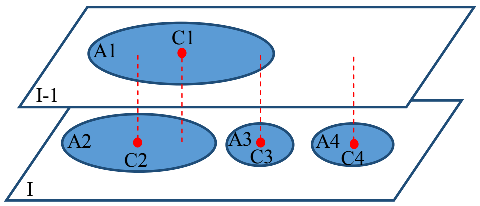
1) *Skeleton Extraction:* The definition of skeleton here is the combination of all the centroids of the air chambers in each scan of CT data. To do so, each of the CT scans in the complete VCT dataset is first turned it into a binary image where the in-blade air chambers are represented by white pixels (intensity = 1). This is done by first thresholding the original data to get Fig. 2 (b). Then morphological closing is performed on the thresholded result Fig. 2 (b), which closes all the openings. Then all the holes are filled in image Fig. 2 (c) to get a complete outline of the blade as shown in Fig. 2 (d). By adding up image b and d, Fig. 2 (e) is obtained where pixels with value of 1 represents air chambers inside the blade. These pixels are extracted into Fig. 2 (f). Since morphological closing have effect on edges, noises can be seen in Fig. 2 (f). Therefore morphological opening is performed on Fig. 2 (f) to get Fig. 2 (g) which is perfect for calculating centroids as shown in Fig. 2 (h).



(a) Original CT scan
(b) Thresholded CT scan
(c) Thresholded CT scan after morphological closing
(d) (c) after filling holes
(e) (b)+(d)
(f) Pixels in (e) with intensity of 1
(g) (f) after morphological opening
(h) Thresholded Air image with centroids marked in red

Fig. 2. Process of Detecting Centroids from a Single CT scan

This operation is performed on each CT scans. While doing so, centroids of layer I are first compared with air chambers in layer I-1. If each centroids of layer I fits into an air chamber in layer I-1, the respective centroids of layer I and I-1 are considered to be from the same branch. If multiple centroids (e.g. C2, C3 in Fig. 3) belong to the same air chamber (e.g. A1 with centroid C1) in layer I-1, this is considered to be the start of a fork where two new branches begin. This connectivity between C1, C2 and C1, C3 is recorded during the process. If a centroid in layer I does not belong to any air chamber in layer I-1, centroids in layer I-1 will be compared with air chambers in layer I whose centroids do not overlap with air chambers in layer I-1. Each overlap is treated as a proof of connection and whenever a branch is connected to more than one branch, it is considered as a fork. If no overlap is found, the air chamber in layer I is considered a new branch (e.g. C4 in Fig. 3). New IDs will be assigned for new branches.



C2, C3 belong to new branches connected with C1
C4 belong to a completely new branch

Fig. 3. Examples of Branch Assignment

2) *Data Representation:* The skeleton is recorded with two tables. One for recording x, y and z coordinates of the centroid and the branch ID it belong to. The second table records connections between branches. Note that because of the top to bottom assignment of centroids to branches, centroids in branches also have the top to bottom order. This way, the specific connection between branches can be accurately described using 'Branch ID From' and 'Branch ID To'. (e.g. Branch ID From = 1 and Branch ID To = 2 means that the last centroid of branch 1 is connected with the first centroid in branch 2)

TABLE 1. CENTROIDS LIST WITH BRANCH ID

Branch ID	Centroid x Coordinate	Centroid y Coordinate	Centroid z Coordinate
1	562	285	6
1	562	285	7
…	…	…	…

TABLE 2. CONNECTION LIST WITH BRANCH ID

Branch ID From	Branch ID To
1	2
1	3
2	4
…	…

B. *Unwrapping*

a) Unfolding (Polar Coordinate Transform)

After the skeleton of the blade is calculated. It is then possible to unfold the blade data from a certain air chamber using the branch points inside that chamber as the origins.

First, a point is selected in the skeleton where the unfolding will be performed. Based on the selected point A0 (X0, Y0, Z0), the unfolding process will start from CT scan No. Z0-29 to No. Z0+30 so that a total number of 60 CT scans are unwrapped. For Θ = 0° to 360° with an increment Δ=0.5°, calculate the D(Θ) as the distance values from all metal pixels to the origin point A in a clockwise (CW) direction and plot them on the polar plot as shown in **Error! Reference source not found.** (b). After applying this to all 60 scans, each results are stacked together to generate a volume data as shown in Fig. 5. Note that this unfolding is not necessarily perpendicular to the middleline but to the CT scan surface as this makes it easier to navigate back to original CT data from the unfolded result.

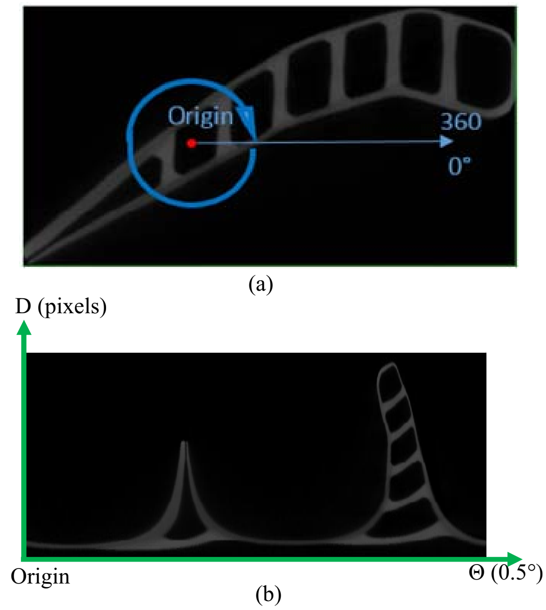


Fig. 4. Unwrapping of a CT scan. (a) CT Scan S1. (b) S1 after polar coordinate transform

b) Flattening

As can be seen from Fig. 5 (a), the unwrapping process successfully turned the original data into an inside-out view. In order to help make the unwrapping/peeling process easier, the internal surface need to be flattened close to the Θ-Z plane.

First, the unwrapped data is converted into vertical slices as shown in Fig. 5 (b):

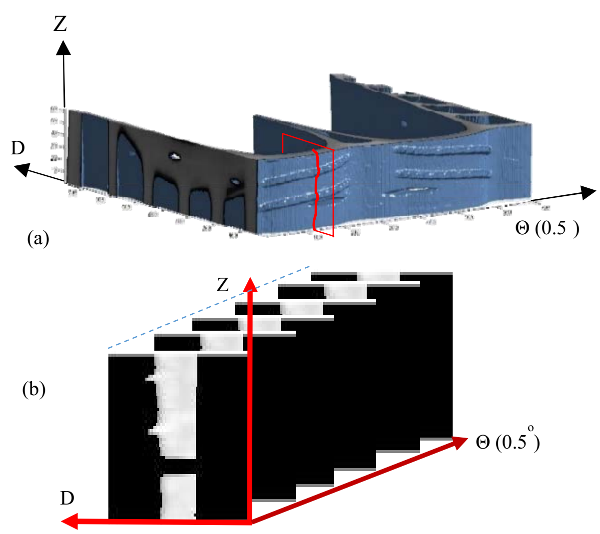
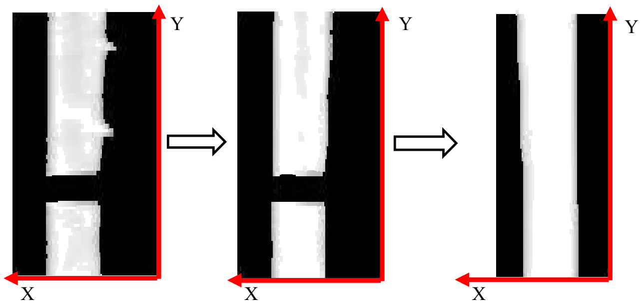


Fig. 5. (a) 3D Rendering of Stacked Unfolded CT scans & (b) Vertical Slices from (a)

Then, for each vertical slices, morphological opening is applied on it to remove the 'spurs'. This is followed by morphological closing with a focus on the vertical direction to close potential 'gap' as shown in Fig. 6.



(a) Original Vertical Slice (b) 'spur' removed (c) 'gap' closed

Fig. 6. Removal of 'gap' and 'spur' in Vertical Slices

The boundary line $x=A(y)$ of the original image Fig. 6 (a) is calculated using (1).

$$A(y) = \begin{cases} \min(distance)\ from\ white\ pixels\ to\ Y\ axis & ,\exists I(x,y) \neq 0 \\ 0 & ,\forall I(x,y) = 0 \end{cases} \quad (1)$$

Then the same method is applied to Fig. 6 (c) to find the boundary line $x=C(y)$. By comparing the boundary line $A(y)$ (in green) of original image Fig. 7 (a) and the boundary line $C(y)$ (in blue) of Fig. 7 (c), a new boundary line $D(y)$ (yellow in Fig. 7 (d)) of the original image can be calculated using (2).

$$D(y) = \begin{cases} A(y) & ,if\ |A(y) - C(y)| < 1\ pixel \\ nearest\ interpolation\ of\ D & ,if\ |A(y) - C(y)| > 1\ pixel \end{cases}$$
(2)

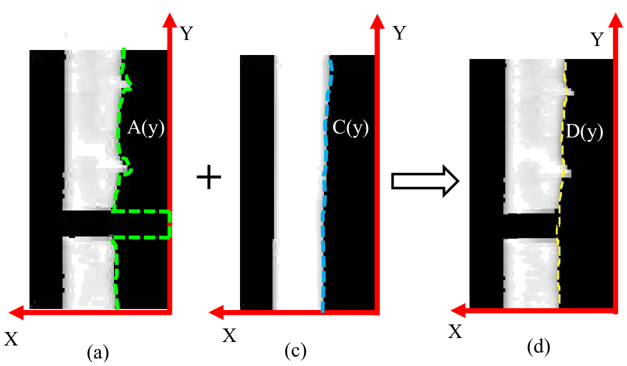


Fig. 7. Calculation of Boundary Line.

By using the boundary line $D(y)$ as a reference, for each y value, the pixels on row y are translated horizontally so that the pixel on boundary line $D(x)$ is moved to line $X=c$ (c is a constant, shown as red line in Fig. 8 (e)). This adjustment from the original image I to the new slice image I' is described by (3). (Result as Fig. 8 (e)).

$$I'(x,y) = I(x+\Delta, y)\ ,where\ \Delta = c - D(y)$$
(3)

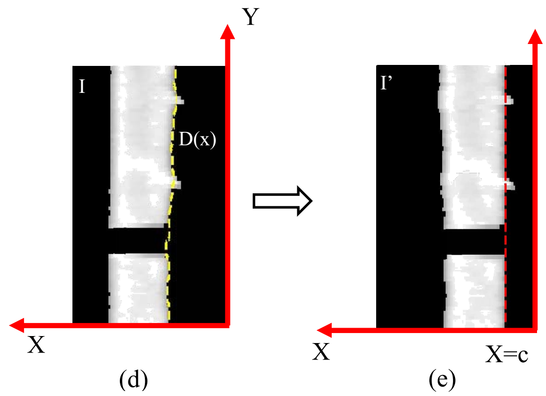


Fig. 8. Row by Row Translation of Pixels

By reassembling all the adjusted vertical slices, the unwrapped data will be flattened as shown in Fig. 9.

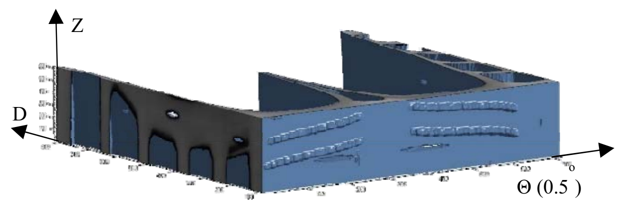


Fig. 9. 3D Rendering of Interior flattened unfolded CT data

c) Movie Generation

The unwrapping movie is needed to assist the inspection process of human expert. This is done by obtaining the data slices in Z- Θ plane as frames of the movie from $D = 0$ to $Max(D)$ with an increment of 1 (as illustrated in Fig. 10). If an anomaly is detected, the inspector can easily navigate back to the original CT data with the occurring angle Θ and Z coordinate of the anomaly.

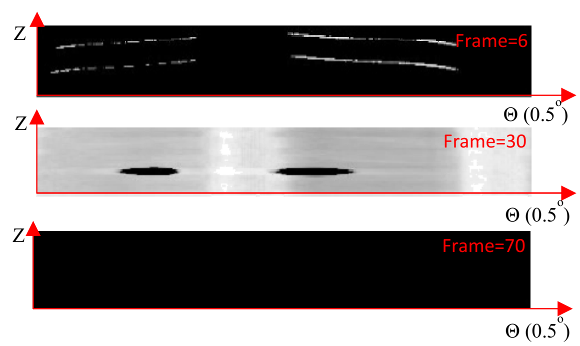
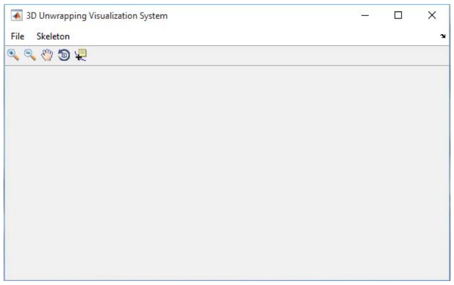


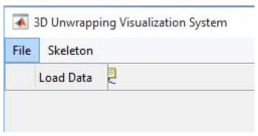
Fig. 10. Frames of generated unwrapping movie

V. Results

A MATLAB program with simple GUI is built. It supports basic functionalities such as Data loading, Skeletonization, 3D rendering, Viewing navigation and point and click unwrapping as shown in Fig. 11. Results generated from VCT data is illustrated in Fig. 12.

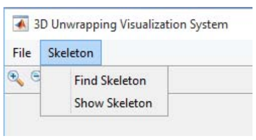


(a) GUI

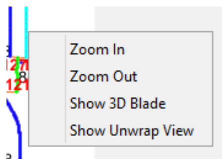


(b) File Menu

(c) Viewing navigation toolbar

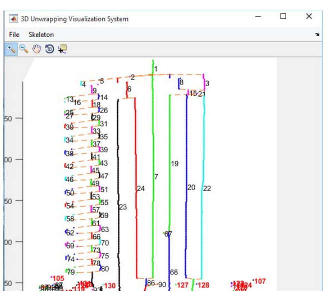


(d) Skeleton Menu

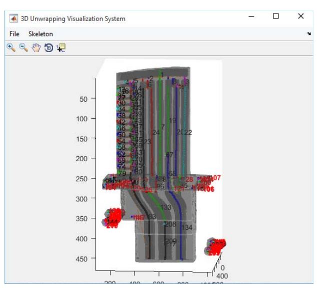


(e) Context Menu on figure

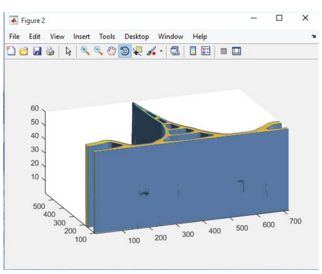
Fig. 11. GUI of Built Software



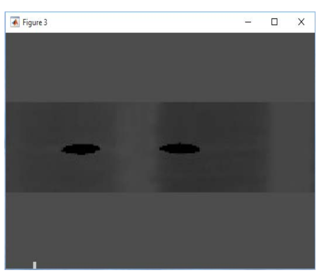
(a) Extracted Skeleton



(b) Skeleton overlaid with 3D Rendering



(c) Unfolded and flattened VCT data of 60 CT scans around user selected point



(d) Unwrapping Movie of (c)

Fig. 12. Skeletonization and Unwrapping Results

VI. Conclusion

In this paper, we proposed a 2D interior surface unwrapping system based on unfolding techniques used in medical imaging field. We have implemented a graphical user interface to extract the skeleton of the CT data for visualization and provide ease of navigation of data to generate 2D interior surface unwrapping representation. The system was tested with real industrial volume CT data and the result was acknowledged by human expert from GE.

VII. Future Works

1) To improve the robustness of this system, enable it to process new blade data with potentially more complicated design (smaller drilled holes, stronger curvature).

2) To improve the unwrapping method to enhance the sampling resolution and accuracy.

3) To improve the flattening method to generate smoother image that reveal anomalies more distinctly.

4) To design and implement automatic detection algorithm based on the unwrapped and flattened result to detect anomalies.

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