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REVERSE ENGINEERING USING COMPUTED TOMOGRAPHY

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INTRODUCTION

We developed a straightforward way to transform x-ray computed tomography (CT) data into an engineering model in a Computer Aided Engineering (CAE) software package. Engineers use such reverse engineering techniques to compare the component “as-is” to the component “as-designed.” Reverse Engineering is also useful when the documentation for components is lost or the component has been shaped by hand for design (as in automotive bodies) or to fit into a location.

In the last three years, several papers reported uses of CT-based reverse engineering [1-7] and described similar techniques [8-13]. Most of these articles, with the exception of Viceconti, et. al. [13], describe CT scans of complicated objects such as gears and automotive transmissions. These complicated objects require complicated and expensive computer programs to perform the transformation. These transformations also require much “hands-on” engineering time to make a reputable CAE model. Here at Los Alamos National Laboratory, we have been asked to scan a smooth metallic hemispherical shell that requires much simpler software and, in principle, much less “hands-on” time than reported in the other work.

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We transfer data from a CT reconstruction to Pro/ENGINEER™ (Pro/E), a CAE software package. Thus, we create an engineering model that we can interrogate for physical properties.

We extract the points that define the surfaces by thresholding the CT values in the reconstructions of the slices. We next enter the data into Pro/ENGINEER™ by transferring these (x,y,z) point coordinates (point cloud) to Pro/E. We transfer both the inner and outer surfaces.

In Pro/ENGINEER™ we create a solid model using the boundary defined by the outer surface of the hemishell. Then we subtract the volume defined by the inner surface. We use the resultant solid model in Pro/ENGINEER™ in any way an original CAD design can be used. For example, we can (1) redesign the hemishell, (2) generate .stl files to make rapid prototypes, (3) generate tool paths for machine tool fabrication, (4) calculate mass properties, and (5) compare the manufactured shell with the original CAD design, if it exists. The accuracy of the model in Pro/ENGINEER is limited by the accuracy of our CT scanner.

COMPUTED TOMOGRAPHY

Computed tomography, often called CT or CAT Scan, displays internal structures. By measuring the x-ray attenuation through an object along many paths, computer programs can construct a density map of the object.

For example, imagine a loaf of sliced bread. A CT scanner could measure the attenuation through each slice by rotating the loaf along its long axis. The scanner measures the attenuation for many paths at each rotation angle. Then this information is reconstructed to show the internal structure in an image of each slice. However, the slice is not viewed from the side of the loaf, but from the face of the slice. These images are reconstructed without physically slicing the loaf.

The slices are 2-D density maps and give very accurate positioning information within the plane. By creating several slices, a true 3-D volumetric image of the object can be built up. The 3-D volume data can be "sliced and diced" to provide any desired cutaway view of the object so that both density and position can be analyzed. In practice, CT scanners are used for a wide variety of objects, including automobile transmissions, compressor vanes in jet engines, and human bodies. Scanners are available today that scan the entire object (many slices) in a single rotation.

STRAIGHTFORWARD PROCESS

We use a straightforward process using our own software and Pro/E to create a solid model in Pro/E (Fig. 1) from our CT reconstructions. The reconstructed data from our x-ray CT scanner is stored slice by slice in a two-dimensional array of pixels. We use a program written in Interactive Data Language (IDL) to find the edges of the part. We format the data into .ibl format to transfer the data points, or point cloud, to Pro/E. Two files are created: one of the outer shell surface and another of the inner shell surface. We create a solid model of the outer surface in Pro/E (Fig. 2) and then subtract the model of the inner surface to leave a hollow shell (Fig. 3).

Straightforward Process Using IDL and ProEngineer

Fig. 1. To create a solid CAE engineering model, we (1) find the two edges that define the surfaces of the hemishell in each reconstructed CT slice, (2) format the (x,y,z) data that define the surfaces, (3) read the data as two separate objects into Pro/E from an .ibl file, and (4) create the model in Pro/E by making solid models of each surface.

Create Solid Model Using the Boundaries Defined by CT Data

Outer
surface

Fig. 2. Solid model of the simulated outer surface of a complete hemishell. Because our CT scan was interrupted after 17 slices, we only worked with a ring of data. Here, we show a solid hemishell made by simulating a noiseless CT data set and by transferring the data to Pro/E.

Carve Out Interior Space Using CT Edge Data

Fig. 3. The interior space is carved out of the simulated model shown in Fig. 2. To carve the interior, we used the interior surface defined from the simulated CT data.

During the CT scan of the hemishell, the 450-kV x-ray head on our CT scanner failed on the eighteenth slice. Thus, for this example, we show only a ring (Fig. 4) that corresponds to the open end of the hemishell. Figure 5 is a photo of the complete shell.

To find the edges of the shell, we estimate that the center of the ring is the center of the array. Then we construct 100 equally spaced radial lines from the estimated center (Fig. 6). Along the radial lines, we create 128 data points with the same spacing as that existing along the abscissa and ordinate in the array. We estimate the effective pixel values of these new points by interpolating the pixel values from nearby data points. We find the edges (Fig. 7) by using a threshold equal to

$$\text{Threshold} = [(\text{the maximum pixel value along the line} - \text{the minimum pixel value}) * A] + \text{minumum pixel value.}$$

We originally used $A = 0.5$. However, we are now using $A = 0.6$ because Odesanya and Mohr [12] reported that 0.6 gave more precise locations of the edges. We fit these edges to a circle using a least-squares technique and verify the circularity of the edges from the goodness of fit. Then we generate new smoother edges by using the fit parameters. We convert these edges from radial coordinates to rectilinear coordinates (x,y) . We also compare the centers derived from the fits for all the slices to ensure that the fitting process is consistent. Using the location of the CT slice as the z parameter, we transfer the edges as (x,y,z) data points to Pro/E as an .ibl file. Edges from successive CT slices are stacked together in Pro/E to form a surface. The CT reconstruction and the Pro/E model are compared in Fig. 8, and the format of the *.ibl file is given in Fig. 9.

Once the data are in Pro/E, one engineer spends about four hours of “hands-on” time to create the solid model. However, we believe we can write a script file that will remove the “hands-on” interactions and make this an automated operation for similarly shaped hemishells without complicated features.

Fig. 4. Pro/E solid model of the scanned region of the hemishell.

Fig. 5. Photograph of the entire hemishell.

Estimate the center.

Construct radial lines with equally-spaced points.

Data is interpolated from adjacent points.

Fig. 6. To find the surfaces in each slice, we (1) estimate the center of the hemishell slice, and (2) create 100 radial lines through the surfaces. In the slice view, the surfaces appear as edges. Along the radial lines, we create 128 equally spaced data points whose values are interpolated from adjacent points in the reconstruction.

Fig. 7. We identify the two surfaces by finding the 60% thresholds along the radial lines. In this simulated example, we plot the CT value at each of the data points along a radial line (see Fig. 6). We chose our threshold to be 60% of the maximum value of the optical density along the line.

CT Data Transformed to Pro E

CT Reconstruction

Reverse Engineered Model
in Pro/E

Fig. 8. Comparison of the three-dimensional CT reconstruction (left) and the engineering model in Pro/E (right).

ibl Format Example

Closed	Index	Arclength	
Begin section !	1		← Header
Begin curve !	1		
35.1947250	0.0000000	0.0000000	← First slice
35.5728111	2.2380517	0.0000000	
35.3706741	4.4683552	0.0000000	
.			
.			
.			
35.1947250	0.0000062	0.0000000	← Repeat first data point
Begin curve !	2		
36.7354507	0.0000000	1.0000000	← Second slice
37.1093063	2.3347197	1.0000000	
.			
.			
.			
Begin curve !	9		← Last slice

Fig. 9. The structure of the .ibl Format.

FULLY FUNCTIONAL CAE MODEL

The model created in Pro/E is a fully functional CAE model. For example, it can be interrogated for physical properties. It can be used in any way that an original CAD design can be used. For example, we can (1) redesign the hemishell, (2) generate .stl files to make rapid prototypes, (3) generate tool paths for machine tool fabrication, (4) calculate mass properties, and (5) compare the manufactured shell with the original CAD design, if it exists.

We had a rapid prototype made from our model. The prototype showed us a scaling problem in our IDL code and some jagged features that were not apparent in the Pro/E display on the computer monitor. The scaling problem was easily fixed. The jagged features are partially because of the 1-mm-thick slices of our CT scan, and most of the jaggedness was removed using smoothing features in Pro/E.

SUMMARY

We have reverse-engineered hemispherical metal shells from computed tomography reconstructions using our own software and Pro/ENGINEER, a CAE program. We do not use any commercial software except for Pro/E. Our hemishell example is successful because it is made of only one material, has simple, smooth surfaces, and does not contain any complicated features such as gear teeth. We create solid engineering models by locating the surfaces in the CT reconstructions and transferring the surfaces to Pro/E as point data. The CT-derived CAE models can be interrogated for physical properties.

We plan to measure the precision of the CT-derived models, as compared to the designed models and to develop ways to improve the precision of the CT-derived models.

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