X-RAY COMPUTED TOMOGRAPHY FOR GEOMETRY ACQUISITION

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INTRODUCTION

X-ray computed tomography (CT) uses penetrating radiation measurements from many angles about an object to reconstruct cross sectional images of the object interior [1-2]. The images are two dimensional maps of the X-ray linear attenuation coefficient for small volume elements in the object defined by the effective X-ray beam size. The CT images provide quantitative measures of component feature dimensions and density as related to the linear X-ray attenuation of the material under study.

The quantitative dimensional measurement capability available in CT image data is analogous to drawing cross sections. The CT data is digital, allowing processing for edge finding with dimensional accuracies to sub pixel values in the original image. CT dimensional sensitivity to 0.01% of the object size is possible. The digital data format can be used not only in NDE workstations but can be transferred to design workstations. By converting the CT data to computer aided engineering/design (CAE/D) workstations, the engineer/designer can access the as-built component geometry.

In the case of components that do not have adequate drawing documentation, the CT data provides a highly cost effective approach for geometry acquisition, i.e. generating digital format dimensional documentation. Multiple slice CT data may be used to completely define the object, or CT data at selected orientations may be used to define specific features. Once data is transferred to a workstation, the designer can manipulate the data to create a part drawing.

DISCUSSION

The use of CT images for dimensional measurements is a very common industrial application [3-7]. The logical extension of this capability is to convert the image data into line drawing format for analysis in engineering workstations [8-11]. Creating data files that can be used in (CAE/D) environment is the geometry acquisition process. Geometry acquisition is valuable for parts that are ergonomically, aesthetically or aerodynamically shaped, in order to obtain a digital model of a part whose form could not be defined mathematically in an original drawing. Parts for which drawings do not exist or are not accurate due to processing steps also benefit from geometry acquisition.

Conventional approaches to geometry acquisition include measurement by hand and coordinate measuring systems (physical and optical).
### Table I
Geometry acquisition process steps.

<table>
<thead>
<tr>
<th>Step</th>
<th>Activity</th>
<th>Boeing Code/Process</th>
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<tbody>
<tr>
<td>1</td>
<td>CT scan object and format images</td>
<td>INDERS (neutral file format)</td>
</tr>
<tr>
<td></td>
<td>(transfer CT images into neutral file format)</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Form image contours</td>
<td>IGES1024COLIN</td>
</tr>
<tr>
<td></td>
<td>a. thresholding for edge finding</td>
<td></td>
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<tr>
<td></td>
<td>b. remove collinear points</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Convert to IGES format</td>
<td>CURVEIGES</td>
</tr>
<tr>
<td>5</td>
<td>Transfer to CAD workstation</td>
<td>ETHERNET</td>
</tr>
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</table>

However, these techniques are all external measurements, have difficulty with cavities, have sparse data measurements or a low sampling rate, and may experience difficulties in registration or orientation. CT uses penetrating radiation so that it measures internal and external features equally well. CT also is performed within a known three dimensional space, such that all positions in the object are known relative to an origin. Provided the object can fit within the CT scanner and be imaged without excessive artifacts, CT offers an excellent technique for geometry acquisition.

The process steps for CT geometry acquisition are listed in Table I. First, the object will be scanned on a CT system. The object may be scanned with one or more single slices at various planes or locations on the part, or in a series of scans which covers the part three dimensionally. The first case would apply to parts that have global symmetries and which may also have regions where particular geometric detail is needed. The second case would apply to parts that have a continually varying, undefined geometry, such as an ergonomic or aesthetic design. At Boeing, initial processing of the scans is performed using the INDERS NDE data processing software [12].

The INDERS software allows the conversion of CT images from any suitable CT system to a neutral file format for handling in subsequent steps. After the CT grayscale images are formatted, the IGES1024COLIN code will create contours. This code typically operates on 1024 x 1024 images. The process of finding the edge contours is to use thresholding. A threshold of the 50% value of the CT numbers between the material and air is taken as the position of the edge. Thresholding works well for objects that are made of a single material [10]. When multiple materials are present at different locations along the edge of a part, a single threshold value may be correct for one material but will not be correct for the other. In this case, more sophisticated techniques are required, such as edge gradient algorithms. The contours that are generated consist of piecewise linear strings connecting points and contain a very large number of points. The data set can be compressed by removing collinear points. The collinear point compression algorithm moves along each contour in the file, removing the middle point in a set of 3, when it is sufficiently close to the straight line between the first and last point to be considered collinear. The collinearity is a variable selected by the operator. Typically values in the range of 0.0001 to 0.001 inch are selected.
Once the contours have been defined from each of the CT image cross sections, the cross sections are converted to the Initial Graphics Exchange Standard (IGES). The IGES format allows the cross section files to be transferred and read by CAD/CAM workstations. In the transfer, each CT slice is put in as a different layer in the CAE/D workstation. Essentially, the IGES files are piecewise linear strings containing points which have x, y and z values. When a series of CT slices are used to evaluate the object the slice height is z, so each layer will have a different z value.

While the geometry acquisition process is reasonably straightforward in terms of data acquisition and data processing, it is important to realize that this is not a fully automated process and that engineering judgement is required. There are several reasons for this. First, the final geometry of an actual part will consist of its design plus the variation that occurs during manufacturing. Thus, if one obtains the as-built part geometry, it is exact for that part, but it is not necessarily the correct design. Second, when the contours from the CT data have been transferred in the CAD/CAM workstation to form a model, they are still in piecewise linear strings. These are very large data files in the workstation. Therefore, the contours should be converted to straight lines, radii and splines and combined into one element. Engineering judgement is important at this point to use acceptable approximations which will simplify the model without adversely affecting the form, fit, function or manufacturability of the part. Third, depending on the part shape, material and CT system, the artifacts in the image may be severe enough to influence the local shape of the part in the edge finding algorithm. Artifacts are often a problem with parts that contain very long, straight sections. Engineering judgement can be used to correct the influence of common CT imaging artifacts on the geometry. Finally, CT may not define a complete part if only a few CT slices are used at various planes within the object. Fiducial marks or key features in the object must be recognized by an engineer in order to properly orient and utilize the cross sections in creating the CAE/D model.

CT actually overdefines the geometry in the piecewise linear strings. The workstation engineer will essentially extract information from the CT data to obtain the final model. It should be noted that it is much easier to delete information in a workstation than to generate input data, so CT data reduces the design effort when building a model of an existing part. The CT geometry acquisition data can essentially be used as templates for redefined contours in the workstation.

EXAMPLES

An example of using CT for geometry acquisition is the B-17 tail wheel, of which only four tail wheels remain in existence and there are no known drawings. One of the tail wheels was structurally evaluated using CT as part of an aircraft restoration project. The part is shown on the CT system in Fig. 1. In addition to evaluating the internal quality of the cast aluminum tail wheel, Boeing took several CT images to provide the essential information necessary to construct a digital solid model.

Three longitudinal and two circumferential slices were taken to provide the information necessary to build the model. Fig. 2 shows a longitudinal CT slice data set after being transferred to a CAE/D workstation. At this point, the CT image has been converted into two contours. The tail wheel is essentially a cylindrically symmetric part. An axis was defined midway between the bearing races on both ends of the part. Only 1 of the 2 contours was needed for further processing so one contour was deleted. Using this single contour as a template, a new contour line was created using straight lines, radii and splines. Engineering judgement is used to simplify the model without altering form, fit and function. This new contour was swept around the axis of symmetry to create a solid.
Other CT slices were used to define details in the tail wheel and assist the designer in creating them correctly in the model. The web, boss and valve stem holes were details required for the tail wheel. The geometry acquisition of the valve stem hole demonstrates the value of CT. Fig. 3 shows the contour of the CT slice through the valve stem hole. The size and angle of the hole was easily determined from this data. However, on the actual part such a measurement would be considerably more difficult, particularly when determining the angle of the hole. In the workstation, a cylinder of the correct size and orientation was constructed and a boolean subtraction was performed on the solid model of the tail wheel to "drill" the hole out.
The solid model of the complete tail wheel is shown in Fig. 4. The design engineer was able to create this model in less time and with greater accuracy, because of the CT generated data, than would be obtained from traditional approaches.

Fig. 3. CT data showing the valve stem hole.

Fig. 4. Solid model of the tail wheel in CAE/D workstation.
The tail wheel example has shown the use of selected CT slices for defining a part and building the drawing. In the case of a complete ergonomic shape, many CT slices may be required. An example of CT for geometry acquisition of an ergonomic shape is an aircraft flight control wheel. Fig. 5 shows the model of the control wheel obtained from 196 CT slices through it. The data has been transferred to a CAE/D workstation.

In this case, many CT slices are needed to define the shaped surfaces. The large CT data file model allows the designer to visualize the part very well. Also, the CT data provides interior features for this model that has a hollow core. This information would not be available from conventional dimensional measurement data acquisition approaches. From this model, the designer will extract new contours by cutting through the data set at the necessary planes to define the part, connect new contours from the data points and build a surface and/or solid model. The final model can be compared to the CT model for accuracy. For a hand shaped part, very similar to that in Fig. 5, designers saved over 600 hours (50% savings) by using the CT data rather than optical measurements for geometry acquisition.

SUMMARY

Computed tomography is extremely well suited and valuable for geometry acquisition. It provides measurements of both external and internal features. Ergonomic, aesthetic and aerodynamically shaped parts, as well as parts for which drawings are unavailable, benefit from the process. Although data reduction and transfer can be performed by computer routines, engineering judgement is very important in the evaluation of the model on the CAE/D system. The engineer can reduce the data sets into simple models by choosing appropriate straight lines, radii and splines to fit to the piece-wise linear strings provided from CT. Also, engineering judgement is used to select the correct orientation of cross sectional plane data, and to eliminate artifacts from the data. Cost savings using CT have been found to be significant over other approaches for geometry acquisition for complex objects that are suitable for CT examination.
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REFERENCES


