Industrial Computed Tomography in Reverse Engineering Applications

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Abstract

In the last years, industrial computed tomography (CT) in Switzerland had its main application in scientific examinations. Specific fields of interest were flaw detection, analysis of failure, dimensional measurements of not accessible geometrical features, inspection of assemblies or statistical investigations of material properties as density distribution. Single slices were taken at well-defined places and used for further analysis.

Today, the most important application of CT has become scanning for 3D-digitizing purposes. First of all, automotive and motorcycle industries as well as their suppliers and the medical technology show a very strong interest in the new possibilities that CT offers. Using this new technology it is possible to reduce the time to market for development of new products. Thus companies can realise substantial competitive advantages.

This paper is about the experiences made working with CT data on parametric CAD, namely with commercially available software tools. For the creation of point cloud data from CT data, it was necessary to develop new algorithms, because the existing tools did not provide satisfying results. Creation of point clouds for first article inspection of aluminium cast parts has become an everyday business at EMPA.

1 Introduction

Reverse Engineering is a term used to describe the creation of a digital dataset based on a physical representation, inverting the regular process of going from an idea through CAD construction to a product [1]. There are several ways of digitising a three dimensional object. Tactile and optical measurement systems require surfaces and geometrical features that are accessible or visible. However, CT can show internal structures as well.

CT data can be processed directly in the form of point clouds or as tessellated surfaces (e.g. triangulated STL files). Segmentation of surfaces must take place in all
three dimensions to avoid discontinuous changes in z-direction as it is the case in contour extraction done slice by slice. Adequate algorithms have been developed at EMPA in corporation with the Swiss Federal Institute of Technology (ETH) in Zurich. Furthermore, the tomogram data can be used to detect porosity, cavities or cracks in casted parts.

First article inspection procedures of cast parts / foundry products are carried out today by comparing point cloud data to the CAD dataset. Deviations can be shown as colour maps on a three-dimensional view as well as slices in any required orientation. Compared to traditional methods of first inspection procedures, the usage of a CT point cloud is almost faster and less expensive.

Transforming CT data into CAD systems with the tools available today is still a lot of work and therefore offers a big development potential. It is especially useful if CAD data of a product don't exist. In future the rendering of a 3D-CAD dataset from 3D-tomograms for simulation and finite element analysis will be even more important. The reason why is the fact that the true object geometry instead of a theoretical model will serve as a base for computation.

To provide services in the field of reverse engineering to their customers, EMPA, ETH and FHBB have set up a network. EMPA is operating an industrial CT for eight years now. ETH and FHBB have the necessary experience in CAD and rapid prototyping and work with the corresponding software tools.

2 Available CT-System and Software for Reverse Engineering

2.1 CT-System

The industrial CT scanner of EMPA made by Scientific Measurement Systems, Inc. (Austin, Texas, [www.sms-ct.com](http://www.sms-ct.com)) was installed in December 1990. It consists of the following main components:

X-ray source: Philips MG 451, 450 kV / 2 mA at spot size 1 mm, oil cooled with oil / air heat exchanger

Detector system: Linear array detector consisting 125 CdWO₄ scintillators and tungsten collimator

Object positioning unit: Handles objects up to 500 mm diameter, 600 mm height and 25 kg weight

Computer system: Sun Ultra Sparc workstation (user interface and image analysis), DEC ALPHA workstation (image reconstruction), Pentium personal computer (data acquisition purposes).

The detector size allows fan beam tomography (third generation) up to 250 mm object diameter. Typical scanning times using this mode of data acquisition are between 2 and 3 minutes per slice. For larger objects translation tomography (second generation) is required. This mode of operation takes more time, typically between 8 and 10 minutes.

The vertical scanning range today is 300 mm. This means that for objects of more than 300 mm in height two passes are required. EMPA will increase this range to 750 mm in 1999.
2.2 Software-Tool for Reverse Engineering

For reverse engineering a tool was applied which is known in automotive and aerospace applications:

Software: "Surfacer", Version 9, Imageware Corp.  
(www.iware.com)

Operating System: Windows NT

Hardware: Personal Workstation Intel Pentium 450 MHz, 
Graphic Board: Elsa Gloria Synergie

3 Applications

3.1 Point cloud generation for first article inspection procedures

Today, point cloud data are used as a link between different methods of digitising and the CAD representation. They are used as well as a base for comparisons in first article inspection procedures of cast products.

Looking at computer tomogram data as a mathematical function that assigns a certain value of density to each volume element, the 3D-surface of the object is an isosurface, consisting of points with the same density (the same threshold value). By using 2D-image processing methods, it is possible to extract a pointwise defined outline of each slice. Stacking these dotted 2D-outlines will result in a 3D-point cloud.

One disadvantage of this method is the effect of creating gaps where the surface is almost parallel to the slices of the tomogram. True 3D-segmentation eliminates this drawback. The newly developed algorithm refers to the slices below and above and uses this information to calculate a linear interpolation of the density values. The resulting point cloud will be an approximation of the isosurface in sub pixel accuracy.

Fig. 1 Point cloud generation: 2D method (left) and 3D method (right)
Going from a stack of tomogram slices to a point cloud considerably reduces the amount of data, however the files are still very large. For further reduction of file size, the points are sorted lexicographically. Along with the data, the customer receives a small utility that he can use to extract the desired number of points.

### 3.2 Reverse Engineering on a motorcycle engine cylinder

In December 1997 a racing engine manufacturer asked the Basel Institute of Technology (FHBB) to do the following task: A cylinder should be designed for the highest possible efficiency for a three-cylinder machine starting from an existing four-cylinder engine. The intention was to gain considerable knowledge about measurement technology and data transformation based on this industrial order.

Data acquisition from the existing cylinder made of aluminium was performed at EMPA with an accuracy of 0.2 mm. From 516 individual tomograms IGES contour data were produced. The contour data were imported from the FHBB into the CAD program I-DEAS. In order to ensure that the geometry could be expressed as parametric objects, the CAD basic elements such as lines, circles and arcs had to be redesigned for the best possible approach to the contour data. With the aim of obtaining better efficiency, the CAD-model constructed was adapted under the supervision of the customer. The modified volume model was subsequently transferred via the IGES interface to a service company for rapid prototyping, ACTech in Freiberg/Sachsen (Germany).

There the volume data was investigated to ensure that it met technical casting specifications. On the CAD system CATIA the form separation was determined and the gating and rising system designed. Then the CAD data prepared for the casting process was converted to a format that could be read by a laser sintering system. Using this system break sand moulds and cores can be built in the so-called Direct Croning®-Process without the need of a pattern. Resin coated sand is hardened in layers by a laser beam. After casting the cylinder was machined, then fitted with the functional components and finally subjected to a standard measurement program on a test bed. The cylinder showed no indications of failure.

![Motorcycle engine cylinder: single tomogram and contours of some slices](image-url)
The way to get a CAD model from CT data over the IGES-Interface was a very extensive process. At this time of project it was the easiest and safest method. Only one commercial software (from Materialise www.materialise.com) was available, excluding the tools from CT manufacturer who has some software to handle the CT data and export it in neutral formats (IGES, VDA, etc.).

The software development in reverse engineering has made large progress within the last 1½ years. The philosophy of the software industry to work only with native geometry formats like NURBS (Non Uniform Rational B-Splines), Bezier and so on has changed. So nowadays it is possible to generate toolpathes (CAM, Computer Aided Manufacturing) and finite models (FEM) based on triangulated geometry formats (STL). Therefore it is expected that great progress will take place in the reverse process chain within the next few years.

3.3 Reverse Engineering of a cylinder head

In November 1998 Rautenbach Aluminium-Technologie GmbH (Wernigerode, Germany) contacted EMPA with the following task: new tools had to be manufactured for the water jacket core of a cylinder head in aluminium being in production for several years now. Unfortunately, there were no 3D-CAD data, only 2D drawings existed. The intent was to perform a reverse engineering procedure, transforming the CT data into the customer's CAD-system (ProE).

3.3.1 Data acquisition

The cylinder head dimensions were 450 x 300 x 150 mm. At the moment the CT system of EMPA has a vertical range of 300 mm only. Hence the object had to be digitised in two partial scans. A total number of 946 tomogram slices with a spacing of 0.5 mm and a pixel size of 0.2 x 0.2 mm were carried out. The scanning parameters used were 450 kV at 2 mA and a brass filter of 1.5 mm thickness. The data acquisition took place during several days.
The x-ray room is equipped with a ventilation system to discharge the waste heat of the x-ray tube. Due to the long scanning time the room temperature rose up. In order to keep the temperature of the high voltage generators within safe limits the process was paused several times and an additional axial ventilator was installed.

The problem was now to fit the two partial tomogram data sets in a common coordinate system. This was done by using reference parts (small bars) made of the same material as the cylinder head. Five bars were fixed with polyurethane foam on the object: three near the middle plane and one at each side. The two partial scan sets were performed from the opposite sides towards the middle plane. Thus in every tomogram stack four reference bars were visible. After determining the positions of all five bars on the tactile coordinate measuring machine at ETH, it was possible to compute the necessary transformations.

![Single slice tomogram of the cylinder head with reference bar](image)

Fig. 4 Single slice tomogram of the cylinder head with reference bar (see mark)

### 3.3.2 Determining the threshold value of segmentation

Up to now, the exact threshold value was determined manually by the operator. Measuring of distances out of the tomograms and comparing them with the measured distances at the object did this process.

Now the reference parts described above were also used for this task. The bars were manufactured with an accuracy of 0.02 mm. The segmentation of the bar surfaces was performed with an initial threshold value. With the segmented data it was possible to compute the size of the reference bars. Comparing the computed size with the exact size led to a correction of the initial guess of the threshold value. By applying this process iteratively we got the threshold value in a prescribed tolerance. The only interaction the operator had to do was to tell the system the position of the bars in the two tomograms and their exact dimensions. The rest was done automatically by the system.
3.3.3 Reducing the amount of data

A CT scan produces a lot of data. The tomogram in our example had 946 slices with 1600 x 1000 pixels each. Every pixel was a four byte floating-point density value. Hence the whole tomogram contained about 6 GB of data. To reduce the data two strategies were applied:

1. The water core was not the only surface to the given threshold value. Instead of generating a point cloud from all surfaces of the cylinder head and isolating the water core from this point cloud, it was better to perform a segmentation of the required surfaces. By extracting the appropriate region of interest, the data was reduced to about 1 GB.

2. A further strategy is to guess a threshold value which is too low and one which is too high. Now only the pixels between these threshold values and their neighbours are stored using some run length encoding. This helps to compress the data without losing required information to compute the surface data.

These methods should be applied before any further operations are performed. It saves not only disk space; it makes the following data handling easier and reduces time for data transmission to other computer systems. Therefore, a set of graphical tools was developed. With these tools the segmentation of the water core out of the 946 slices was done in about five hours.

3.3.4 Point cloud generation

After performing the data reduction methods described above the point clouds of the upper and lower water core were generated using the 3D linear interpolation algorithm. With the transformations, which were determined from the positions of the reference bars, the two partial point clouds were fitted into a common coordinate system.

Fig. 5 Point cloud of water core
3.3.5 Reverse Engineering

The point cloud was imported into the software tool “Surfacer” from Imageware Corporation. Afterwards the data set was placed in a xyz coordinate system. This was realised with constructed planes based on segmented point groups. Due to the symmetry of the model, half reduced the huge number of points. The next step was to define different subsets of points that describe a small part of the whole object.

On these subsets nurbs-surfaces were created with the smallest number of surface degrees. The single surfaces were applied to build sets by using surface boundary conditions mainly tangency. The complete closed surface set should finally describe the volume of the water core. Additionally the core mark prints have been constructed and added to the model. The biggest problem was the measurement differences of the 2D drawing and the finished object. It resulted from the casting process and the manual work of the modeller. The preparation is still in progress; the time for the whole process will be approximately 5 weeks for an experienced user.

3.3.6 Summary

The following overview shows the required steps of the entire reverse engineering process of the cylinder head:

1. Fixing reference parts with polyurethane foam on the object
2. Data acquisition
3. Measuring reference parts with coordinate measuring machine
4. Computing threshold value from the reference parts’ subtomograms
5. Segmentation of the water core surfaces (data reduction)
6. Computing of the point clouds with 3D linear interpolation
7. Computing the positions of the reference parts from the subtomograms
8. Fitting the two partial point clouds into a common coordinate system
9. Reverse engineering with standard software tools
4 Conclusions

Computed tomography is excellent for generating 3D data of complex cast parts. Aluminium as the mostly used material in engine production can easily be penetrated up to 300 mm wall thickness using a 450 kV x-ray source. The achievable accuracy on objects of 300 mm diameter is in the range of 0.2 mm. An even better accuracy may be possible, due to the segmentation of the surfaces in subpixel range. But up to now there are no systematical investigations on that subject.

Generating point clouds for first article inspection purposes has become a main activity on the CT system at EMPA. Having more and more companies like engine producers and foundries applying this new technology, the rate will probably rise in future. The time saved working this way will lead to competitive advantages under present market conditions.

It has been shown that it is possible to go from CT data onto the CAD. In the case of the motorcycle engine cylinder, the whole process chain has been accomplished up to the new, optimised product. The commercially available software tools still have to improve in functionality. The huge amount of data generated by 3D digitising can sometimes cause problems nowadays. Working with effective algorithms allows reducing file size, progress in performance of computer systems and mass storage devices on the other hand will facilitate the development of this technology.

CT digitising may become an important tool in the field of simulation and finite element analysis. Computations give more reliable results if they are based on data gathered from true physical objects instead of theoretical CAD-models.

References