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Industrial Computed Tomography for Reverse Engineering Applications

Tomographie rayons-X assistée par ordinateur pour des applications de reverse engineering

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Norbert Schuhmann; Lucia Ioana Bolboaca

Abstract
Computed tomography is an excellent device for generating 3D data of complex parts. It allows a complete scanning also of the inner geometry of a complex parts. Since this new measuring technique first was used mostly more for material testing, it was identified as a powerful device for dimensional inspection in the recent years. There, well-known CAD methods, which are currently available in commercial software tools, can be used for a complete and accurate measuring of automotive casting parts - especially parts with a very complex geometry as cylinder heads. The current paper will cover a new reverse engineering application based on a CT measurement of an cylinder head, as it was required by a industrial partner of the authors. The goal was the surface extraction of the water channels of an aluminum cylinder head for the use in flow simulation. By using that example the paper will illustrate, how even complex industrial problems could be solved by using computed tomography and by applying modern CAD tools.

Keywords: *Industrial Computed Tomography, reverse engineering, CAD.*

From CT Measuring of Complex Parts to the CAD Description
In the recent years dimensional measuring complex automotive parts with computed tomography became more and more popular, especially for casting parts as aluminum cylinder heads [10]. Here conventional measurement techniques using a tactile CMM or an optical device like a laser scanner can only measure the exterior surface of the part, but not inner structures of the parts, which are of high interest for instance in the case of automobile cylinder heads. Here e.g. measurement of the minimum wallthickness and the geometrical description of internal cavities like cooling channels is of big importance for the casting industry.

Starting with medical computed tomography devices in the past, special computed tomography devices were developed in the meantime and are available on the market, especially designed for the industrial purposes. Here, high accurate mechanical detector systems, high energy x-ray sources and improved detector systems are used to get as much as possible out of the measurements. In the current project a SMS CT with a x-ray source with maximum energy of 450 keV and a line detector with 125 scintillators was used by the Eigenoessischen Matrialpruefungsanstalt (EMPA) in Duebendorf, Switzerland, to measure a cylinder head casted by the company Bombardier Rotax in Gunskirchen, Austria, which produces engines, mostly for motorcycles and snowmobiles.

The measuring by computed tomography typically results in a large series of 2D greyvalue images, where each image contains all geometrical information of one planar slice through the measured object. In the current case the image slices had a slice distance of 0.5 mm between consecutive images, the pixel size was 0.3 mm^2 and the image resolution was up to 850 x 800 pixels per image with 8 Bit greyvalue information, which are 256 different greyvalues per pixel.

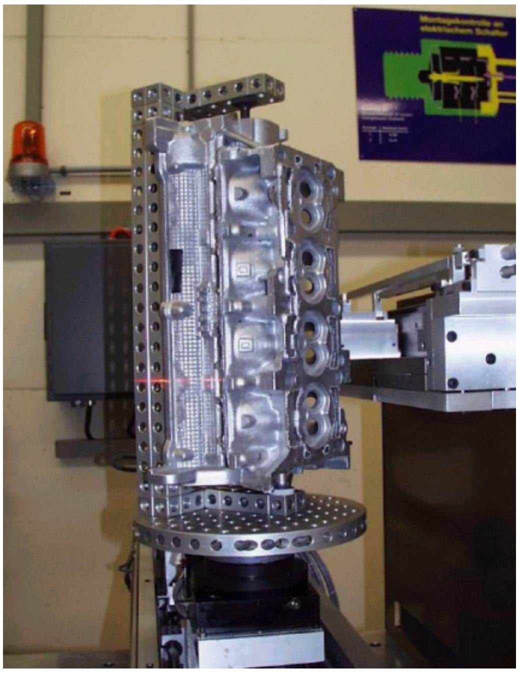

Figure1: Cylinder head with object positioning system

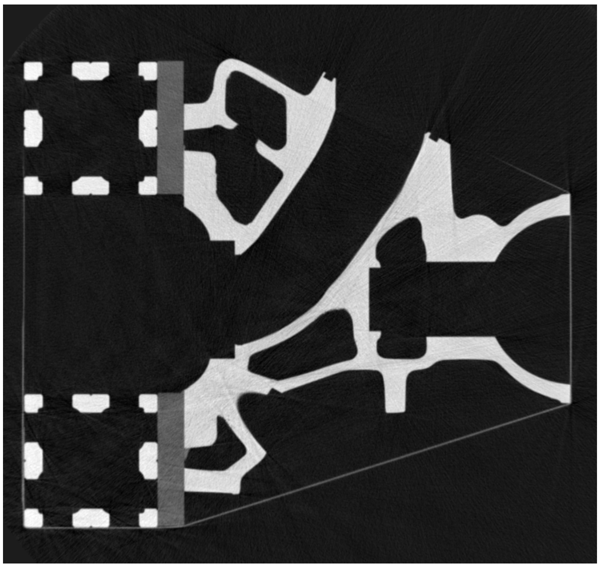

Figure2: Single CT image slice obtained by CT measurement together with object positioning system

For the measurement of the complete part, 902 parallel image slices were recorded. To obtain a CAD description from the CT images, commercially available tools can be used to get a tessellated surface description, also called a polygonized point cloud, which is well known in CAD and especially in Rapid Prototyping. The polygonized point cloud usually consists of a large number of connected triangles, which describe the surface to be extracted. Almost all of the commercially available tools for handling CT images were originally developed for medical applications, but some of them were improved in the meantime to handle industrial CT measurements, which typically contain a substantial higher number of CT images with a even higher image resolution in each image slice. In the current case the software MIMICS V7 of the Belgium company Materialise [8] was used, which already can fulfill industrial requirements. The mathematical method for the generation of polygonized point cloud data from images is the well-known marching cube algorithm, developed in 1987 [3], which segments all images in so-called cubes, where the vertices of each cube are 8 image pixels from two neighbored image slices. Every cube can be triangulated separately by taking into account the greyvalues of the 8 pixels. Triangle reduction methods are typically used afterwards [4] to reduce the number of triangles especially in flat areas of the part to obtain finally a compact polygonized point cloud.

Extraction of Water Channels

The goal of the project for Bombardier Rotax was to obtain a geometrical description not of the part surface, but of some of the internal cavities of the cylinder head: these cavities which are the water channels of the cylinder heads, used for water-cooling of the operative engine. The surface extraction of cavities is almost impossible, when using conventional measurement techniques, since they cannot be seen from outside. In contrary, CT measuring offers the possibility of extracting cavities by applying segmentation methods already within the image slices. With modern image segmentation methods, contours in each image can be extracted. These methods typically result in several distinguished closed contour polylines per image slice. One of them is the outer contour of the part surface and the others describe the contours per slices of the cavities.

Using a region growing method through all image slices, the MIMICS software offers the possibility for automatically connection of contours, which are separate contours in some images and connected in some other image slices, but form together the surface description of the aimed cavity, the water channel. By simply applying this region growing method, a serious problem occurres, which seams to make the extraction of the water channels almost impossible - from a first view. It would work, if the water channel would be totally located "within" the cylinder head, which is of course not the case: The channels have a connection to the surface of the engine head, where they will be connected with the water tubes when assembling the engine. Concerning the CT slices, at least some of the images do not have separated contours, separated in a surface and a cavity contour: In some images these contours are connected. Actually there is no commercial tool available on the market, which offers the possibility to separate the image contour of the part surface and the image contour of the cavity in an automated way. Consequently in the current project this contours had to be separated manually by just adding a rectangle in each of the affected image, which turned out to be some annoying work – but fortunately only some images had to be edited manually, s. figure 3.

The segmented and manually contours in each image slice already form a geometrical description of the water channels, but not represented as a polygonized point cloud. To obtain the latter description, the contours are only used for the segmentation of the series of images into a set of separate pixels, but already through the complete series of the images, here the word voxel is typically used to mention the 3D information of each pixel, which is obtained by the x- and y- (grid-) coordinates in the image together with the z-height of its image slice. Finally, that set of voxels can be polygonized with the already mentioned marching cube algorithm. All steps described here except for the mentioned manual editing can be done automatically by applying tools of the MIMICS software.

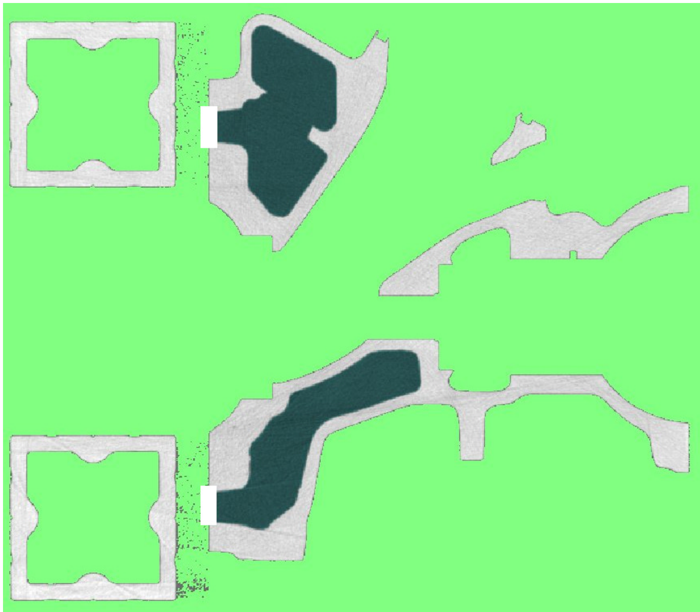

Figure 3: Extraction of cavities by image segmentation, and manually editing, in dark: segmented cavity.

Alignment Methods for the Measurement of Big Parts

Another problem had to be resolved in this project: The size of the cylinder head increased the maximum size to be measured, not in diameter but in the z-height to be operated by the SMS CT scanner. Therefore, EMPA scanned the cylinder head in two records: First from the top until somewhere below the middle of z-height, than turned around the part and finally scanned it again from the top of the turned part to get the lower half of the cylinder head. The result were two sets of CT images, which could not merged just by adding the images, since the local coordinate systems of the two series differ. An alignment of the two sets of images was necessary. In order to apply modern alignment methods currently implemented in state-of-the-art reverse engineering CAD-systems like Surfacer Verdict [2] or Metris CADCompare [5], the alignment was not performed on the images, but on the reconstructed polygonized point clouds. Consequently from each of the two sets of image slices, one polygonized pointcloud was computed, describing (a little be more than) the half of the total water channel. The two polygonized clouds had to be aligned now, which is rotating and shifting one of it, that it fits exactly on the other half.

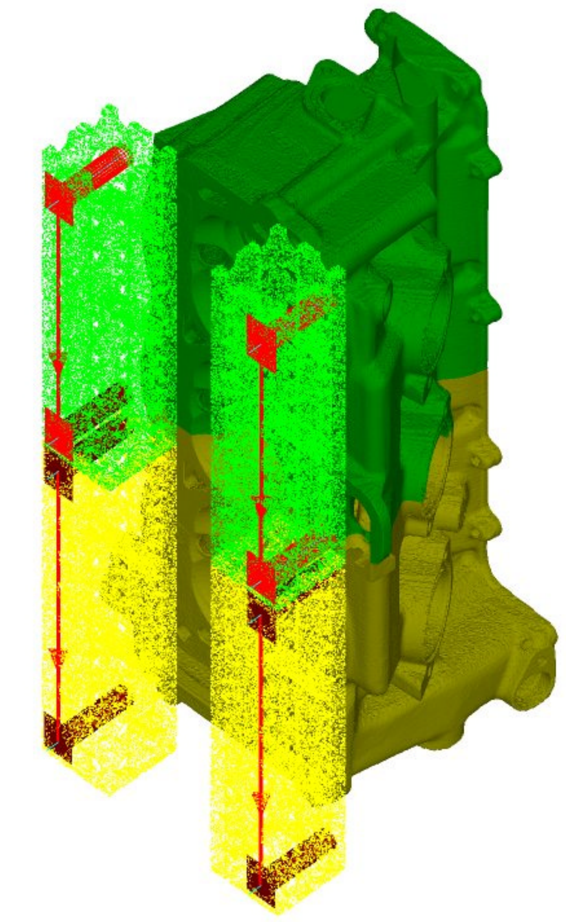

Figure 4: Alignment of tow measured parts, here the cylinder head (not the cavities)

The alignment task is well known in tactile measurement techniques, when (usually before measuring) a coordinate system of the part has to be set with the same origin and coordinate axis as the reference CAD model. In the CAD model the origin and the location of the coordinate axis is typically defined with some features of the part to be measured, the evaluation software of the CMM does the alignment after the relevant measurements were performed. In the mentioned CAD systems Surfacer Verdict and Metris CADCompare a similar procedure can be performed: A small set of geometrical pairs have to be extracted from the point cloud, e.g. three pairs of spheres, three spheres for each of the two parts. The two sets of three sphere centers define a common coordinate system then. Here a different pair type was used, since it could be obtained very easy and which guarantees high alignment accuracy: The cylinder head was fixed on the manipulator of the CT device with an object positioning system. This object positioning system with the same material than the cylinder head (aluminum) consists of several aluminum bars with cylindrical holes to fix the part with them onto the CT manipulator. The object positioning system was also penetrated by the x-ray beam, when the part was measured, and can consequently be seen in the CT image slices, s. figures 2 and 3. The dimensional accuracy of the positioning system is very high with a maximum dimensional uncertainty of 0.01 mm. When turning around the cylinder head, the object positioning system was unscrewed from the CT base plate, but still fixed to the cylinder head. Therefore the relative location of the cylindrical holes to the cylinder head did not change, and consequently features of the object positioning system can be used as reference alignment pairs. The high dimensional accuracy of the object positioning system automatically guaranteed an alignment of very high accuracy, which was verified by computing several sections through the aligned polygonized model without detecting a significant offset between the two measured parts. Figure 4 shows the two parts of the measured cylinder head together with the object positioning system with extracted cylindrical holes, which can be used as reference pairs. The two parts of the water channel were aligned just by using the same alignment map then.

Re-Triangulation Methods

Since both parts describe more than the half of the complete part, an overlap of the two parts could be seen after the alignment. To get rid of this overlap, the overlap in each of the parts was removed first by manual circle selection of the relevant triangles in each part. This resulted in a thin rectangular hole between the parts. With re-triangulation of the triangle vertices at the borders through that rectangular hole, the parts were merged into a single polygonized model. This step was performed with the software MAGICS 6.0 again from Materialise [7], which offers several tools for manual and automatic editing of polygonized point clouds.

Results

The result was a complete description of the water channels of the cylinder head as shown in figure 5.

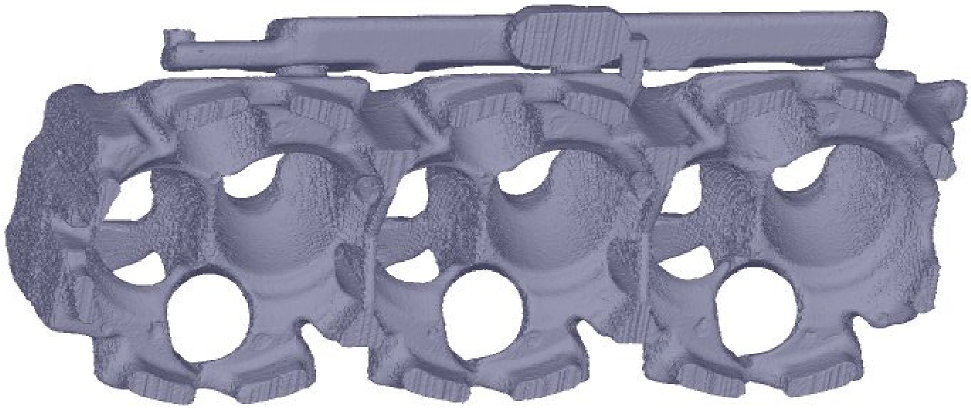

Figure 5: Resulting polygonized pointcloud of the water channels (without overlaps and merged)

Final tests showed, that all normal vectors of the triangle were consistent, no degenerate, no redundant and no overlapping triangles were found, which are typical problems in point cloud polygonizing. Consequently the topological quality of the resulting model was verified as satisfying high.

Summary

The current paper tackles a reverse engineering problem, provided by a industrial engine manufacturer: The water channels of a huge cylinder head had to be extracted and represented as a polygonized point cloud for further use in flow simulation. CT turned out to be a suitable measuring technique to extract the inner water channels of the cylinder head by applying special CT image segmentation methods. Since the part size exceeded the maximum size, which could be measured by the CT system in one record, the measurement was done in two records, each measurement describing one half of the part By applying alignment tools, which are available in state-of-the-art reverse engineering systems, overlaps could be removed and the two parts obtained by the CT measuring were merged. The result was a CAD model in polygon representation of high quality.

The case study showed, that even complex reverse engineering problems of the automobile industry can be solved today by using modern reverse engineering software tools.

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