



MULTI-PURPOSE 3D COMPUTED TOMOGRAPHY SYSTEM

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ABSTRACT

A new flexible and versatile 3D X-ray CT system was designed by means of a modern mechatronics concept using sophisticated precision mechanics, fast electronics and a modular object oriented software structure. The system allows to scan a wide range of component size and material with a single device. With a single scan the three dimensional structure of test sample is reconstructed. About 800 slices are available immediately after the scan is completed. The data include both 3D geometrical and material data allowing for a variety of different methods of analysis. Examples for different materials and geometries ranging from microsurgical components to large castings are given. Applications from flaw detection, geometry measurement and geometry comparison based on 3D computer tomography are demonstrated.

INTRODUCTION

Modern quality standards require NDT technologies which allow to detect flaws as well as deviations from the nominal geometry in any section of components with complex inner structures. Therefore, three dimensional information about material and geometry is required. Such information can be delivered by Computed tomography (CT).

Standard X-ray tomographic systems which are in use in industry as well as in medicine to date are so-called 3rd generation two dimensional scanners. A fan of X-ray generated by an X-ray source penetrates the object and the attenuation is measured by a linear detector (see Fig. 1). In medical tomographs the source and detector rotate around the patient. In industrial applications it is in most cases advantageous to rotate the object. During the rotation a set of one dimensional projections is measured and reconstructed afterwards. The result is a two dimensional image. To get a three dimensional image with such a conventional tomograph, the object has to be moved in the direction of the axis of rotation and several scans have to be performed. A stack of slices has to be mounted to get a three dimensional image. The main limitation of such a system is the long scanning time and the non-uniform spatial resolution in the three dimensions.

Further limitations of typical CT systems used today in industrial applications are the narrow range of materials and object dimensions which can be scanned by a single CT system. Therefore, NDT service providers typically need to operate several systems to offer a sufficiently wide range of inspection service to their customers.

Micro CT systems are in use for non destructive testing of small objects with high resolution. Object dimensions are in the range of some millimetres. Macro or standard CT systems are designed for the inspection of large objects with limited spatial resolution.

Our newly developed CT system RayScan 200 combines the advantages of both systems and overcomes the limitations of 2D CT by implementing direct 3D CT technology. Micro and macro CT was integrated in one system. Fast scanning and reconstruction, high resolution over a wide range of material and object size are the main features of the system that will be described in this article.

CONE-BEAM TOMOGRAPHY

Traditionally, volumetric image reconstruction is achieved through scanning a series of cross-sections (slices) with a fan-shaped X-ray beam, and by stacking these slices. These 2D tomographic scanners make use of linear X-ray detectors, see Fig. 1. For further details on 2D tomography see R.A. Brooks and G. Di Chiro (1). Recently, with the introduction of planar detectors, computed tomography began a transition from fan-beam to cone-beam geometry. In cone-beam geometry the entire object is irradiated with a point-shaped X-ray source, and the radiation attenuation is measured on a detector plane behind the object (see Fig. 2). The primary advantages of cone-beam geometry include reduced data acquisition time, improved image resolution, and optimised photon utilization.

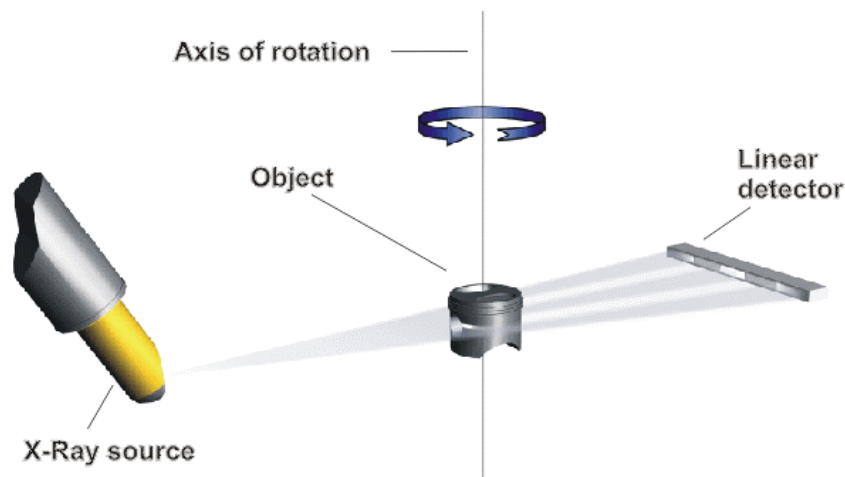


Fig. 1: Principle scheme of a conventional 2D tomographic scanner

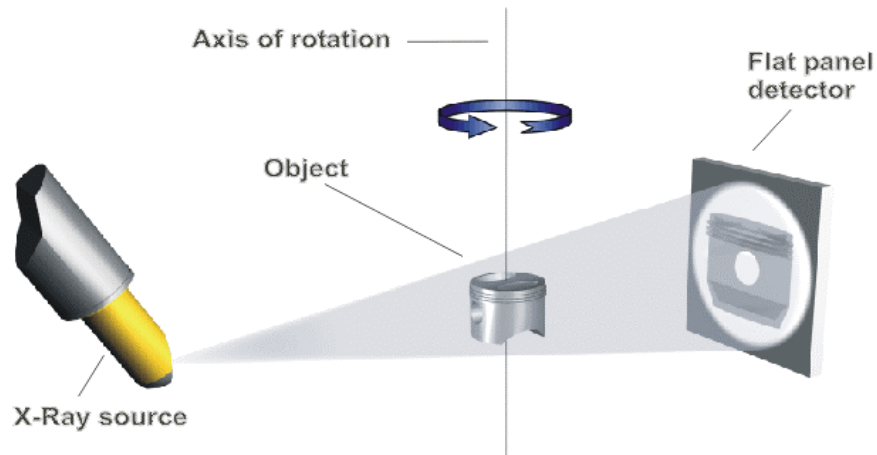


Fig. 2: Principle scheme of 3D cone-beam tomography

Exact Cone-Beam Reconstruction Algorithms

Important theoretical analyses on exact cone-beam reconstruction were done by Smith (2) and Grangeat (3). A sufficient condition for exact cone-beam reconstruction was formulated: if there exists at least a cone-beam source point on any plane intersecting an object, exact cone-beam reconstruction can be achieved. Unfortunately, the most practical configuration, i.e. a circular orbit of the X-ray source does not fulfill the Smith's condition since a plane parallel to the trajectory may intersect the object but not the trajectory. The available projection data from a circular trajectory is confined within a torus shown in Fig. 3. The required projections for an exact reconstruction correspond to the sphere with the center in the center of rotation and a radius sufficient to include the object. The area with missing projection data is formed by the points lying within the sphere enclosing the object but not in the torus of available projections. This is usually referred to as a shadow zone.

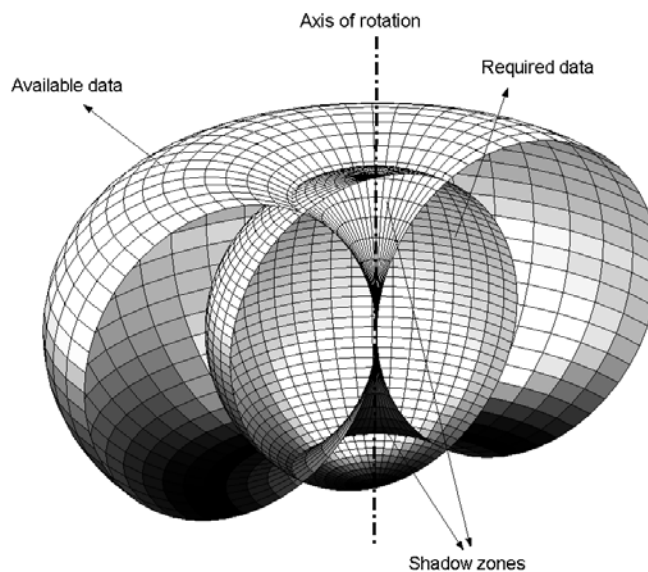


Fig. 3: The circular trajectory measures projections within a torus. The required data set for exact reconstruction lays within a sphere surrounding the object. The unmeasured data are corresponding to conical shadow-zones around the rotation axis.

Various exact cone-beam reconstruction algorithms have been implemented according to Smith's theory and Grangeat's framework. A common feature of these algorithms is the requirement of the collection of a full data set which translates in cumbersome mechanics and huge computer resources needed both in the acquisition and in the processing phases. In addition, in most cases these methods demand that the object is restricted in size, so that its projection never falls outside the available detector. This requirement is not realistic in most cases of computed tomography, like, for example, for long objects.

Approximate Cone-Beam Reconstruction Algorithms

Despite progress in exact cone-beam reconstruction, approximate cone-beam reconstruction remains the best practical approach, especially in the cases of incomplete scanning and partial detection. Furthermore, approximate reconstruction is usually associated with higher computational efficiency, and may produce less image noise and ringing. Feldkamp-type cone-beam reconstruction is the main stream of approximate cone-beam reconstruction (4). The Feldkamp (FDK) cone-beam algorithm is an ingenious adaptation of the weighted filtered backprojection algorithm for equispacial rays.

The unknown distribution function at position (t,s,z) is given by:

$$f(t,s,z) = \frac{1}{2} \int_0^{2\pi} \frac{D_{SO}^2}{(D_{SO}-s)^2} \int_{-\infty}^{\infty} P_{\beta}(Y,Z) h\left(\frac{D_{SO}t}{D_{SO}-s} - Y\right) \frac{D_{SO}}{\sqrt{D_{SO}^2 + Y^2 + Z^2}} d\beta dY$$

where: $t = x \cos \beta + y \sin \beta$, $s = -x \sin \beta + y \cos \beta$, (Y,Z) are the detector pixel coordinates in a plane translated such that the q-axis is superimposed on the z-axis (see Fig. 4).

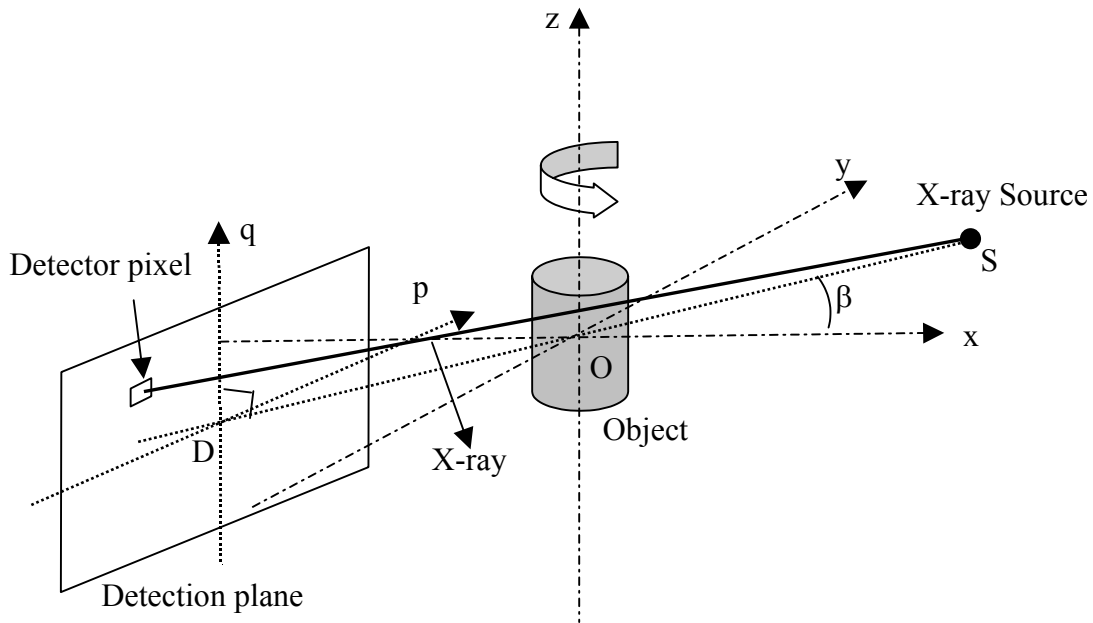


Fig. 4: Conventional cone-beam configuration

Oxyz: reconstruction coordinate system; object rotates around z-axis

Dpq: planar detector coordinate system

SO: source-object distance

SD: source-detector distance

β : angle of rotation of object (equivalent picture – angle of synchronous rotation of source-detector assembly)

The cone beam reconstruction algorithm can be broken into the following three steps:

Step 1: weighting projections

Multiply projection data, $P_{\beta}(Y,Z)$, by the function $D_{so}/(D_{so}^2 + Y^2 + Z^2)$ to find the weighted projections.

Step 2: filtering projections

Convolute the weighted projection with the ramp filter h by multiplying their Fourier transforms with respect to Y . Note this convolution is done independently for each elevation Z .

Step 3: backprojection

Finally, each filtered weighted projection is backprojected over the three-dimensional reconstruction grid. The two arguments of the weighted projection represent the transformation of a point in the object volume into the coordinate system of the tilted fan.

Improved Cone-Beam Reconstruction

The FDK is an approximate method because only those points of the object that are illuminated from all directions can be properly reconstructed. In a cone-beam system this region is a sphere of radius $D_{so} \sin(\Gamma_m)$ where Γ_m is half the horizontal cone angle. Outside this region a point will not be included in some of the projections and thus will not be correctly reconstructed. The main limitation occurs at relatively large cone angles. We modified the Feldkamp algorithm to reduce density errors in planes far away from the middle plane and to achieve low reconstruction times. The software and hardware design was optimized to keep density errors due to the cone angle low.

Currently, the projection data in tomographic systems can be acquired much faster than the data can be reconstructed with serial processing on individual processors. In order to speed up the reconstruction time drastically, we parallelized the algorithm. The main results show that the cone beam tomography problem can be solved in parallel to the acquisition using our parallel version of the reconstruction algorithm. The parallel algorithm allows for a speedup approximately proportional to the number of processors while maintaining a very good ratio of computation time to data transfer time.

SYSTEM DESIGN

The principle of operation of our 3D CT system is shown in Fig. 2. The X-ray cone beam from an X-ray source penetrates the object and the attenuation is measured by a large area detector. In order to irradiate the object from all sides, the object rotates in the X-ray cone. During the rotation a set of projections is measured and stored. The set of projections is used to reconstruct the 3D structure of the object (see previous section).

In order to allow the scanning of a large spectrum of components with a single device, the system was designed for components of dimensions from 5 mm to 600 mm. Highly precise mechanical and electronic components had to be developed in order to achieve high quality results for the whole range of component dimensions.

A six-axes manipulation system made of granite elements with slide units moving on air bearings was developed (see Fig. 5). Together with optical linear measuring systems and a high precision motion controller a positioning precision in the range of one micron was achieved.

In the micro CT mode the object is placed close to the X-ray source. The projection of the object is magnified. A magnification factor of up to 120 with a spatial resolution below 5 μm was realised. In

macro CT mode the object is placed farer away from the X-ray source. A high precision adjustment of the source-object distance over a wide range allows for an optimum projection of the object on the X-ray detector. A horizontal shift of the detector enables scanning of objects with a diameter larger than the detector width. Heavy objects up to a mass of 80 kg can be placed on the rotation table.

X-ray source as well as X-ray detector are moved vertically in parallel to accommodate different object heights. The maximum object height is 1500 mm.

The X-ray photons are generated in a microfocus X-ray source with a maximum voltage of 225 kV. High resolution micro CT requires a focal spot size of a few microns. Besides small focal spot sizes the source can be operated at high power to penetrate larger objects. The detector is made of amorphous silicon coated with a scintillator. It proved to have a dynamic range of better than 75 dB and a linearity of better than 1%.

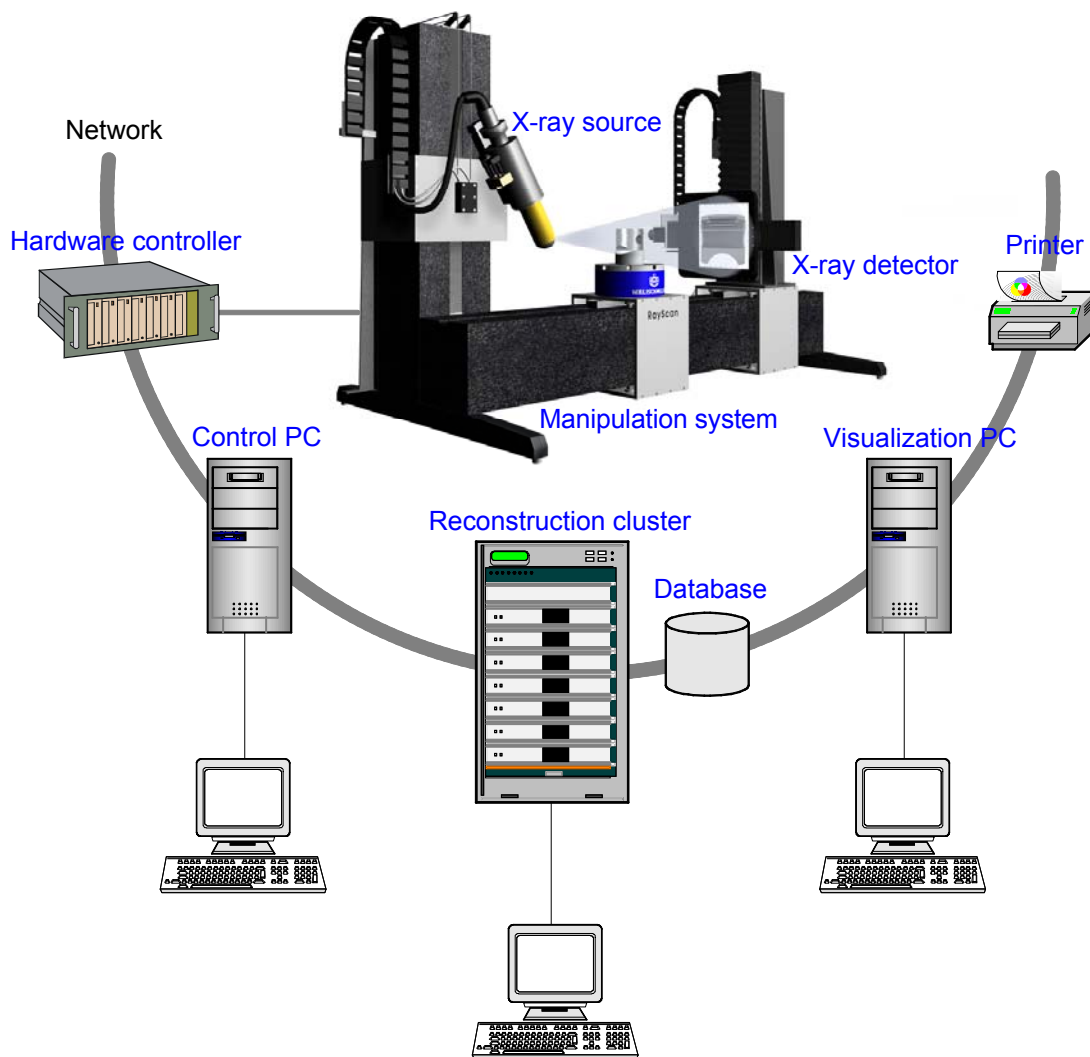


Fig. 5: Main components of the 3D CT system RayScan 200

The system is equipped with three computer systems, the operating system is Windows NT. The control PC is responsible for the control of all components of the scanner as well as the data acquisition. An intuitive graphic user interface with an integrated expert system helps the user to select optimum parameters.

After the start of the measurement the projections are sent to the second computer system, the reconstruction cluster. It is a modular and scalable system which can be equipped with as many

processors as necessary to perform the reconstruction in parallel with the measurement (see previous section). Typically 6 to 8 processors are used for standard applications.

The third computer system has the task to visualise the result and to do post processing operations. Different ways for visualisation and post processing will be described in the following sections.

The data of the system is stored in a data base which ensures that all data and measurement parameters are saved automatically for future use and for the purpose of quality assurance.

An optimisation of the components and their interaction as well as a fine tuning of the system lead to a high resolution 3D tomography system which can be applied to a wide spectrum of objects ranging from 3 mm to 600 mm with a spatial resolution of up to a few microns.

MICRO CT AND MACRO CT

To demonstrate the flexibility of the CT system RayScan 200, the result of two objects of different size and material will be shown. Fig. 6 shows a photography of a microsurgical instrument on top of a pin. It is made of a stainless steel alloy. The width of the instrument is 1.6 mm, the width of the lower part is 0.35 mm. In Fig. 7 the 3D CT reconstruction is visualised. The volume data contains all the details necessary for the material and geometry evaluation.

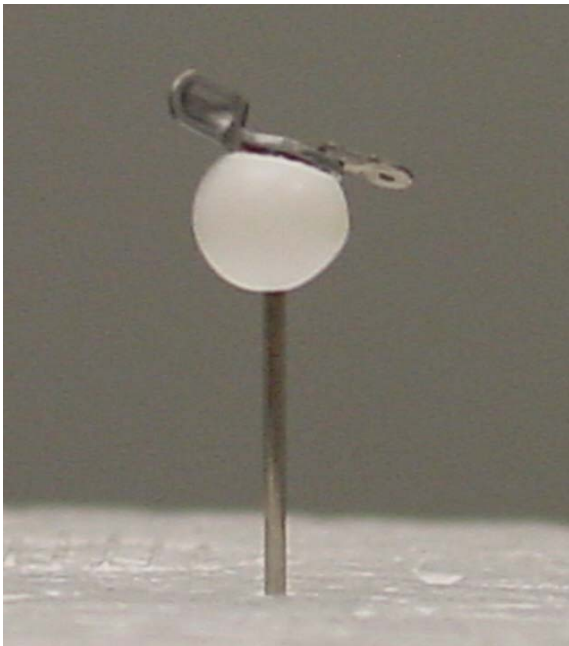


Fig. 6: Photography of a microsurgical instrument on top of a pin



Fig. 7: 3D CT reconstruction of the microsurgical instrument

An example from macro CT is shown in Fig. 8. The height of the aluminium casting is 345 mm. The volumetric information from the 3D CT system can be used for a variety of different NDT tasks which will be demonstrated in the following sections.



Fig. 8: 3D visualisation of an aluminium casting

APPLICATION OF CONE BEAM CT

The reconstruction of the tomography system generates 3D voxel data. It is a three dimensional array with attenuation values which are proportional to the density of the material. Therefore it is possible to analyse the density of the material in any section of the scanned object. Density variations as well as voids, inclusions or other types of defects can be detected. Furthermore, the surface between material and air or between different materials can be derived from the voxel data, thus allowing to analyse the 3D geometry. These analysis features are obtained by post processing software modules. The structure as well as the data flow in shown in Fig. 9. It will be described in the following sections. Further applications of 3D tomography are described in (5).

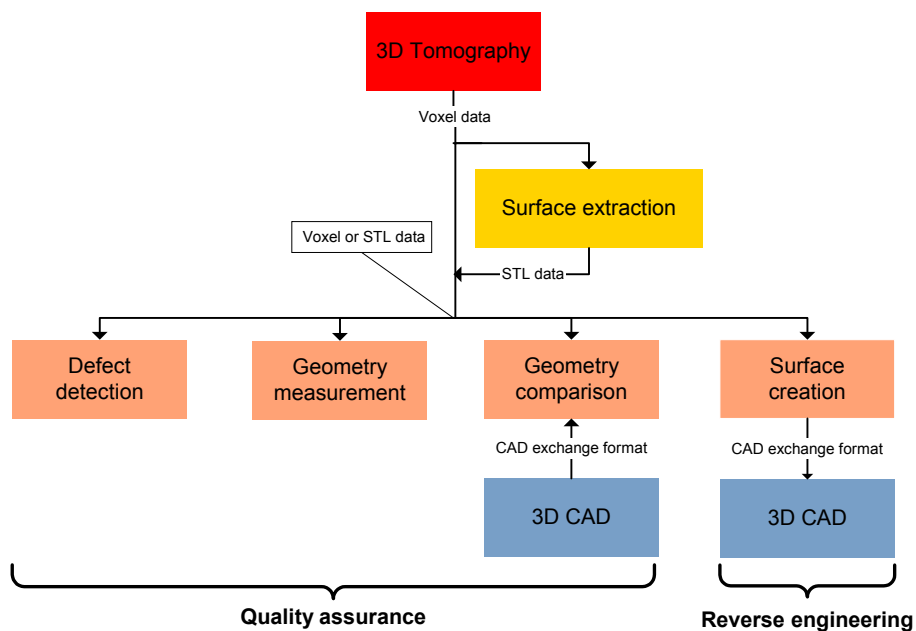


Fig. 9: Application and data processing of 3D tomography

Defect detection

3D Tomography is a non-destructive method that has the potential to detect defects in any geometry. The defects can be detected either by analysing the voxel data utilising 3D voxel visualisation software or by generating isosurfaces from voxel data and analysing surfaces in a 3D surface visualisation software. The generation of isosurfaces is called surface extraction in Fig. 9. The output is stored in an STL format which is the most common exchange format for such kind of surface data. In this section, the defect detection based on a voxel data analysis is demonstrated. The voxel data can be visualized in several ways. It is possible to generate any kind of cuts, slices or isosurfaces.

Fig. 10 shows a 3D visualization of an aluminium casting. Displayed is the outer surface of the object and a virtual cut at the front side. The cut shows the inner structure of the object as it would look like in a real cut. Gas porosity defects are visible. A detailed analysis of the position, shape and size of the defects allow the design engineers to improve and optimise the production process.

Any kind of two dimensional slice in any orientation can be extracted from the 3D data. In Fig. 11 a horizontal slice is shown providing information about the geometry as well as about material defects.

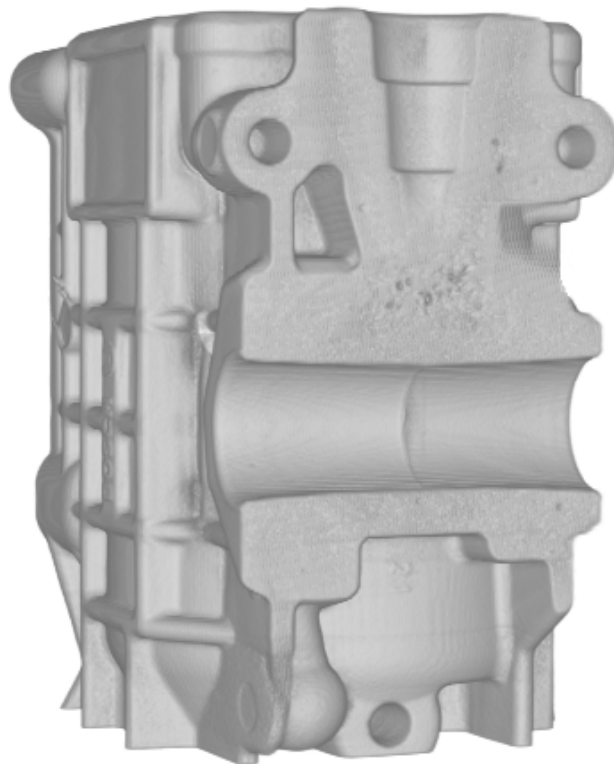


Fig. 10: Visualization of 3D tomography data showing the outer surface of an aluminium casting and a virtual cut at the front side

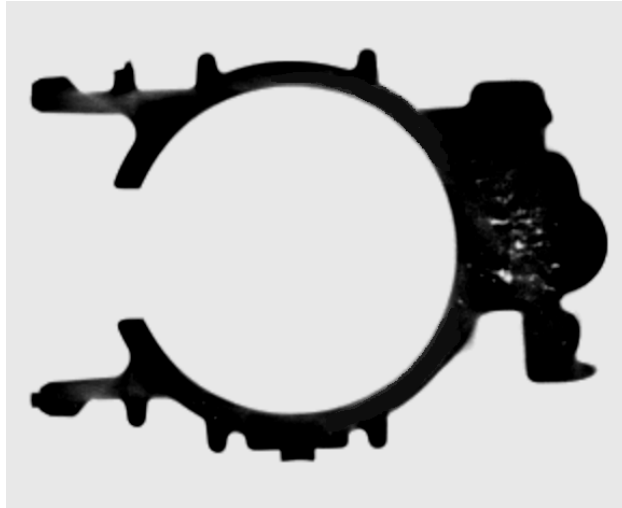


Fig. 11: Extraction of a 2D slice from 3D tomography data

Geometry Measurement

Geometry measurements based on 3D tomography data can be performed either by directly measuring the voxel data or by measuring surface data that was generated in a first step from the voxel data (surface extraction, Fig. 9). In both cases two dimensional or three dimensional measurement can be performed. In Fig. 12 two dimensional measurement based on voxel data is shown. In many cases of quality control the geometry in specific sections need to be measured. For this purpose a two dimensional slice can be extracted from the 3D voxel data and measured using similar functions as in a CAD program. The example in Fig. 12 illustrates how diameters, distances and angles can be determined. Furthermore, the two grey levels show two different materials, demonstrating that the CT system is capable to detect material variations.

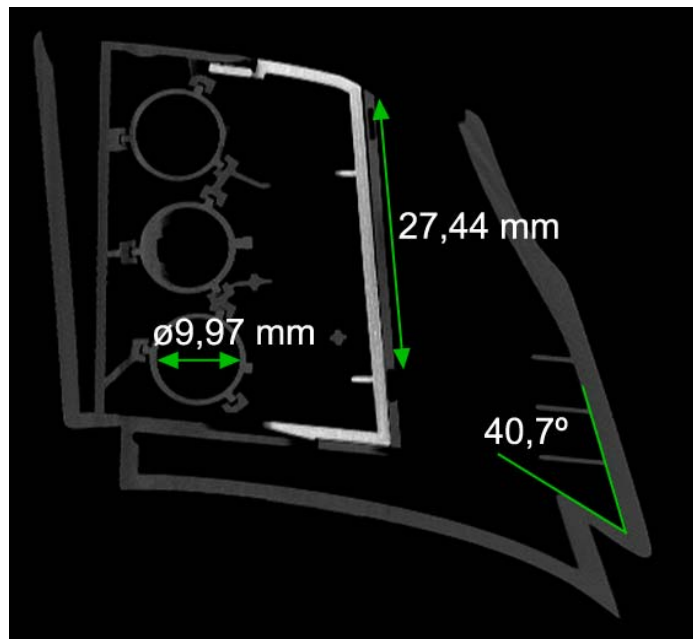


Fig. 12: 2D geometry measurement based on voxel data

In Fig. 13 an example for three dimensional measurement based on surface data is given. Structures on the outside as well as on the inside of the component can be measured. To measure internal structures, the object can be virtually opened by cutting the 3D result.

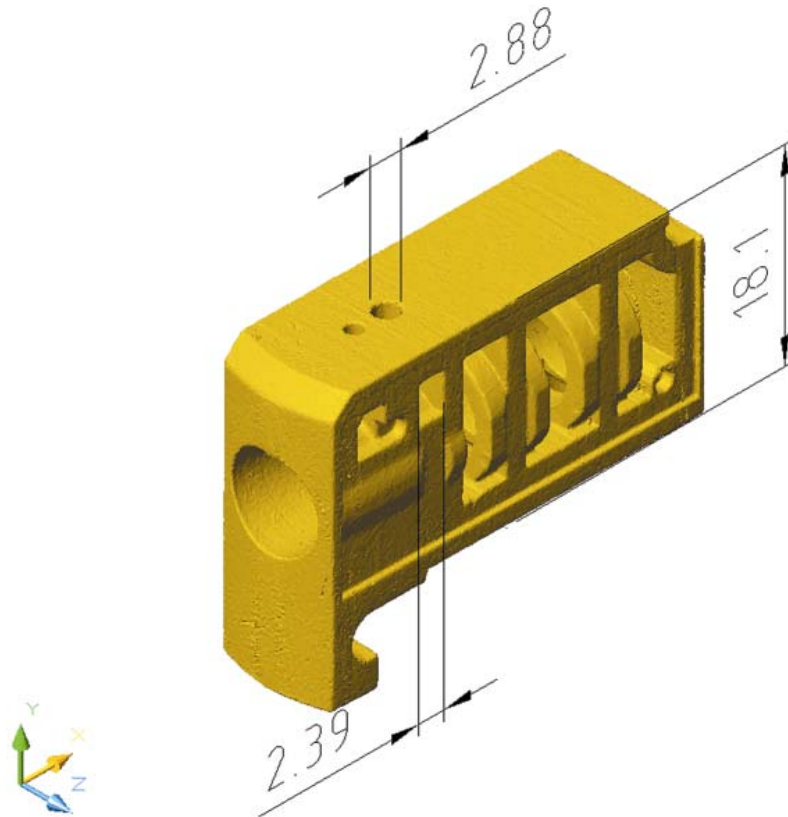


Fig. 13: 3D geometry measurement based on surface data (STL)

Geometry Comparison

In the phase of prototype manufacturing it is essential for the engineers to know the deviation of the manufactured geometry from the geometry of the CAD drawing. This can be achieved either by comparing voxel data from a 3D tomograph to surface data from a CAD program or by comparing surface data generated from the voxel data to surface data from a CAD program (Fig. 9). To demonstrate the geometry comparison, a component was manufactured and scanned in our 3D tomograph. Afterwards surface data was extracted and stored in STL format. Fig. 15 shows the rendered STL surface. If 3D CAD data is available (Fig. 14), it can be compared to the STL surface. In a first step, the two geometries have to be registered, i.e. both geometries have to match in a common 3D coordinate system. There is a variety of different ways to analyse the deviation of the real geometry (measured by 3D tomography) from the nominal geometry (from the CAD system). The deviation can be documented in tables showing statistical data like maximum, minimum and average deviation. More informative are graphical representations like in Fig. 16. The picture shows the deviation in different colours. Positive and negative tolerances are given and the tolerance band can be adjusted to give the maximum information about the deviation. Also shown is a histogram of the deviations based on measurements in 250000 points.

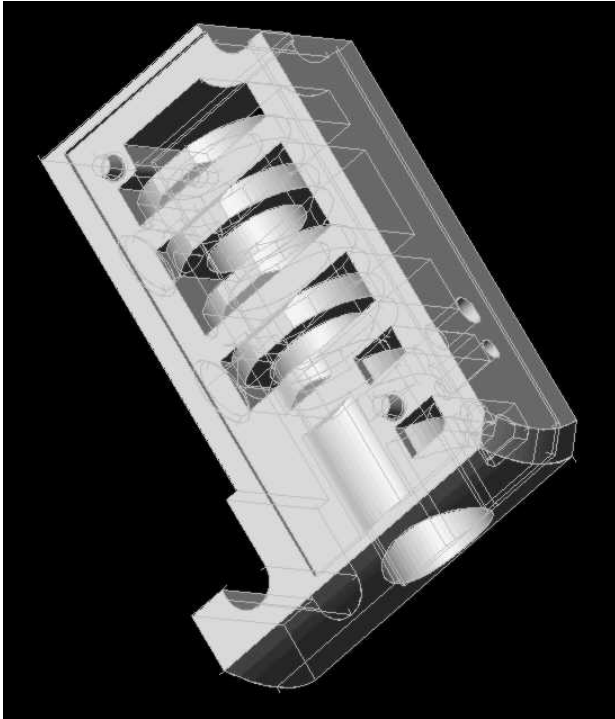
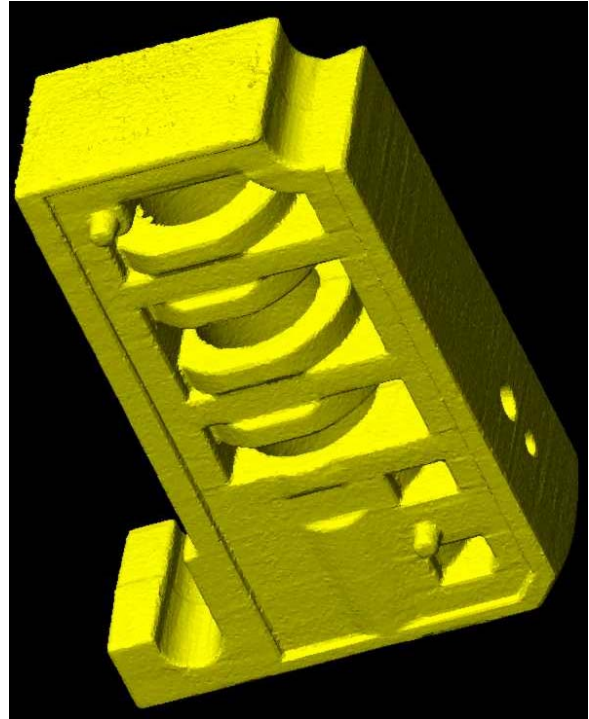


Fig. 14: CAD data



**Fig. 15: Surface extraction from voxel data:
rendered STL data**

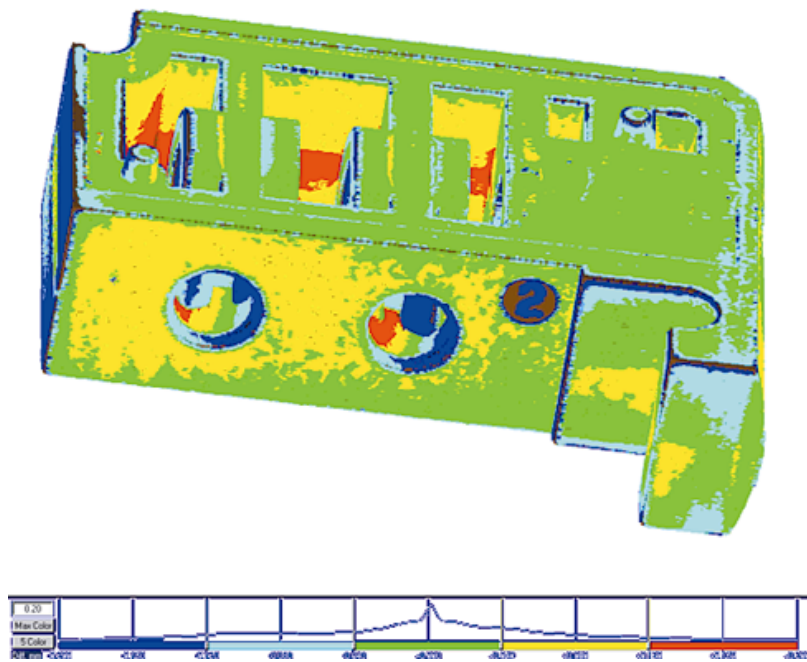


Fig. 16: Comparison of tomography data with CAD data

CONCLUSIONS

The 3D tomographic system RayScan 200 was shown to be a versatile tool for material testing and quality control. Testing and evaluation of a large variety of different materials, geometries, dimensions as well as different kind of analysis features with a single NDT device and a single scan gives new

opportunities to industry as well as research and development in view of fast 3D testing and rapid product development.

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