MODERN VOXEL BASED DATA AND GEOMETRY ANALYSIS SOFTWARE TOOLS FOR INDUSTRIAL CT

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Abstract: Computer Tomography has become a well recognized tool in industrial quality control. Modern computer tomography systems ranging from micro-CT to huge multi MeV systems allow us to generate more and more detailed views of the inner of nearly any object. With the scan resolution becoming smaller and smaller, and at the same time image matrices becoming larger and larger, we are able to localize smallest defects even in large scale objects. At the same time even with the same data set we are able to measure the outer and inner geometry of an object with a measurement point density never known before from classical tactile or optical techniques. However, scanning objects in high resolution generates huge amounts of data, easily exceeding two GByte per scan. These huge amounts of data have caused a major drawback of a wider acceptance of CT technology in industrial use. Either no software tools have been available at all or available software process chains haven't been able to process these amounts of data in reasonable time.
This presentation will introduce a new generation of 3D visualization and analysis software tools for industrial CT users. Interactive visualization of huge data sets with several Gbyte in size has become possible on a standard PC. Automatic wall thickness analysis and internal defect/porosity analysis can be done within minutes. In addition this presentation will also demonstrate the latest generation of software tools for highly accurate 3D geometry analysis based on voxel data.

Introduction: More than one hundred years ago X-ray technology started its triumphal procession when Wilhelm Conrad Roentgen discovered a new kind of radiation in his laboratory in Wuerzburg, Germany in the year 1895. In 1901 Prof. Roentgen received the first Nobel Prize ever consigned. Over the years many inventions driven by the X-ray technology followed as well as many more Nobel Prizes, especially in the medical application field. More then seventy years later the computer tomography has been invented by G. N. Hounsfield in 1971, and again the Nobel Prize for medicine was assigned in 1979 to G. Hounsfield and A. Cormack for their pioneer work on computer tomography. Up to this moment most of the developments on X-ray technologies and computer tomography have been focused on special medical applications. Another twenty years later computer tomography (CT) has become a powerful, well accepted tool in industrial applications as well. Today industrial CT is on its way to become a major tool of industrial quality control in high-tech branches, not only for material testing but for geometry analysis as well. This article will describe the evolution of industrial CT over the last few years and it will present the most modern software tools for voxel data based image and geometry analysis.

Results & Discussion: THE EVOLUTION OF INDUSTRIAL CT
In the late eighties CT became popular as a tool for non destructive testing in industrial applications. At that time CT was used to create two-dimensional cross sections of an object under investigation. The engineers performed visual inspections of a rather small number of slices, e.g. they looked for inclusions within material probes or other internal defects. A typical image size at that time has been in the range of 256 x 256 pixels. In the later 1990s industrial CT became a true 3D imaging technology. Stacks of continuous scanned slice images were created, so that the full volume of an object under investigation became digitized. Therefore 3D quantitative analysis became possible, for instance the measurement of the volume of an object, its surface area or just distance measurements in an arbitrary orientation. At the same time the accuracy of the CT scans became better and better. Today objects with the size of 50 cm in length are scanned at a resolution of 0.2 to 0.3 mm. All these enhancements in CT performance were possible due to more stable and more powerful X-ray sources, better detector systems and enhancements in the complete CT system design. On the other hand the amount of data within a single data set became larger and larger by scanning a larger number of images; in addition the images itself became larger. After a long period where the standard CT image size has been 512x512 pixels, the 1024x1024 pixels image are now a standard size.

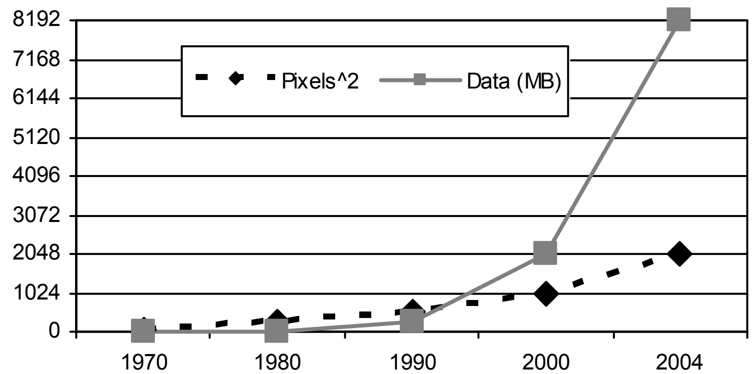

Figure 1, Increase in CT image sizes and data set size.

The increase of the data set sizes accelerated when flat-panel detectors became popular. In our days a 1024x1024 pixel detector produces a 2 GByte data set within an hour or less. Some of our customers produce single data sets with sizes of up to 8 GByte, and are reaching the next limit of CT based object analysis: it is no longer possible to perform a simple slice by slice inspection on a data set of this size, at least not in reasonable time.

TODAY'S CHALLENGES IN INDUSTRIAL CT

Besides the challenge to further optimize the CT systems hardware, its performance and capabilities, the probably biggest challenge at this moment is to process the huge amounts of data resulting from today's CT scanners in reasonable amounts of time. The time to process data sets today easily exceeds the scan time, e.g. data sets as large as 8 GByte already means waiting several minutes to get the data loaded from disk or via a network into a computers memory, not even thinking of the computational time required to perform complex 3D image analysis tasks.

One useful effect for this challenging task, we can still count on, is the continuously growing performance of modern PC hardware. Since Moore's Law is still valid we can assume that PC hardware is doubling its performance every 18 months. But besides faster and faster PC hardware sophisticated software tools are needed to analyze voxel data sets resulting from industrial CT.

Our company - the Volume Graphics GmbH - was founded with the goal to develop and market voxel data visualization and analysis software technology and application software. The first step on our way to application software with the capabilities to process large voxel data sets was the development of a 3D computer graphics technology which is able to visualize the data with interactive performance. Interactive 3D visualization of the object under investigation is a key feature of an ergonomic analysis software tool. Our volume rendering software technology VGL was developed since the mid 1990s to solve this task. Today VGL enables us to visualize data sets with more than 2 GB on a standard PC, and data sets with several ten GB in size on a 64 bit hardware platform with interactive performance. Based on VGL's voxel graphics technology, the application software VGStudio MAX was developed as a tool for analysis and visualization of voxel data.

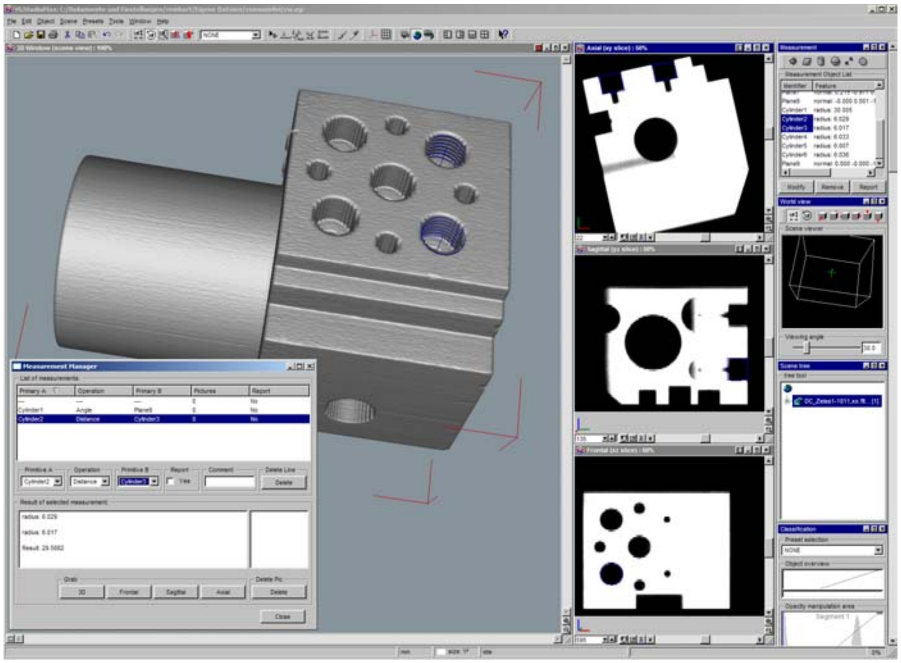

Figure 2, VGStudio MAX user interface.

Besides multiple 2D and 3D visualization capabilities, e.g. 3D clipping, opacity and colour mapping, and arbitrary 2D multi planar reconstruction, the software includes powerful tools for quantitative measurement tasks. Distance, volume, surface, surface area measurement tools, structure analysis for foam like structures are available, as well as 3D image processing, 3D segmentation capabilities and a polygonal iso-surface extraction tool with STL file export. The large variety of tools included in VGStudio MAX enables its users to utilize their voxel data in many application fields, e.g. in quality control, first article inspection, rapid prototyping and reverse engineering tasks.

LATEST DEVELOPMENTS IN VOXEL BASED DATA ANALYSIS

Taking the casting industry as an example, the following chapters will demonstrate how the growing numbers of CT users and their requirements have driven our latest developments in the field of voxel data analysis solutions.

AUTOMATED DEFECT ANALYSIS:

In the late 1990s the casting industry became a major group in Europe's industrial CT users' community. More and more foundries found out about industrial CT and its capabilities in their quality control process. Aluminum castings are somehow ideal objects for CT inspection because they are objects manufactured of a single material which can be sufficiently penetrated by x-rays. One major task in quality control on aluminum castings is the localization and quantitative analysis of inclusions in the casting. These inclusions are typically visible in a CT image as dark closed structures within the material. To analyze such defects we have developed an automated analysis tool. In a first step the tool localizes potential defects by a simple grey value threshold. As a result the CT data will show a binary image with areas containing material only and areas with potential defects. In a second step the volume of the potential defect areas are determined by a connected component and region-growing analysis. Within this step a user defined upper and lower boarder for the defects sizes will eliminate all the area of the outer air and large designed cavities from the list of potential defects. Defects located on the objects surface and therefore connected to the outer air won't be detected by this approach due to the simple upper boarder used for a defect's volume. After the simple defect's volume check a much more complex and sophisticated set of image processing analysis tasks will now differentiate between true defects and structures caused by noise and image artifacts. After all the analysis steps have been passed the remaining areas are classified as defects. Their position within the object, their size, volume and morphology and many more parameters are determined.

All the resulting parameters are displayed in a defect analysis report tool. This tool allows the generation of printed reports with detailed information about each individual defect or statistical information of the whole part, e.g. the total defect volume, porosity or defect size histogram.

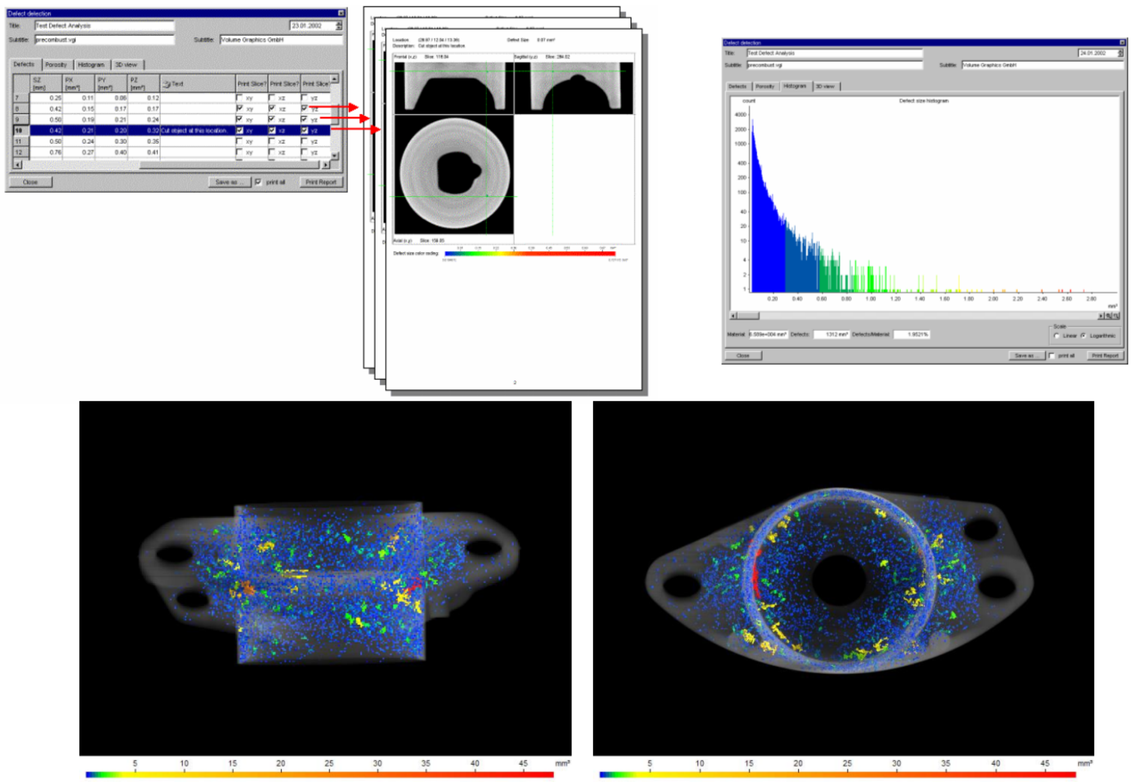

Figure 3, VGStudio MAX' defect analysis report features: defect table, printout for individual defects, defect size histogram, transparent 3D visualization with color coded defect size.

Automated minor wall-thickness detection/analysis:

The second kind of defects the casting industry is interested in, are areas of minor wall-thickness. Caused e.g. by the shift of internal cores during the casting process areas might exist where the wall-thickness under-runs the allowed range. To localize such areas within 2D slice images is nearly impossible for complex parts where walls might run in arbitrary direction in 3D space. A wall-thickness analysis tool working in true 3D is required to solve this task.

Such a 3D wall-thickness analysis tool has been developed and is used today at many customers' sites. To explain the complex underlying image processing routines, we will use a highly simplified image of the process. By moving a "ball" through the voxels of the data set defining the material we will find areas where the ball will hit two neighboring transitions between air and material. At this position we have found an area with the wall-thickness of the ball's diameter.

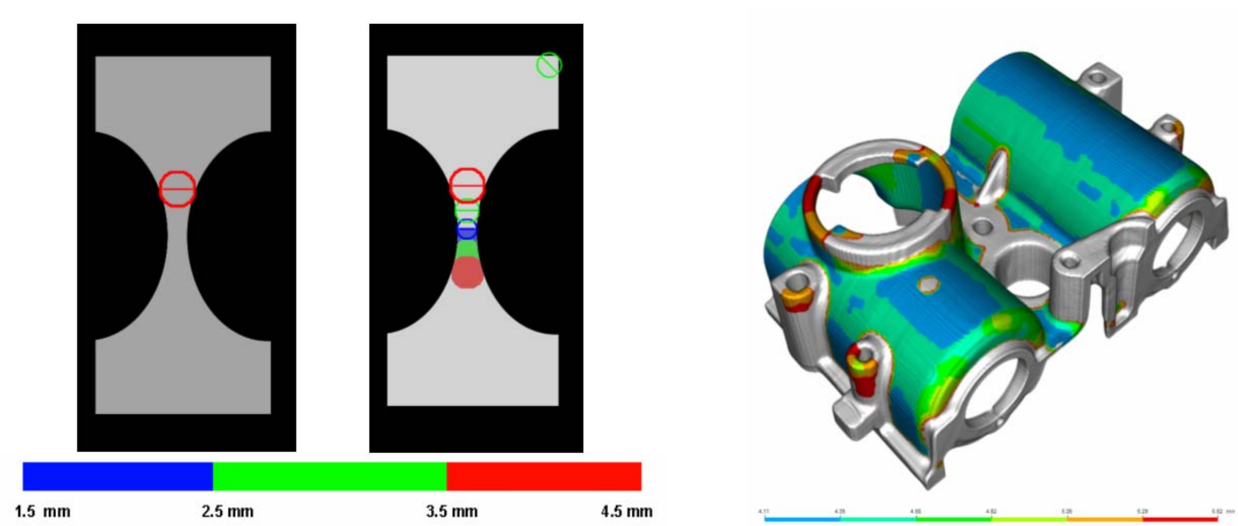

Figure 4, Schematic CT-scan with varying wall-thicknesses (left) and wall-thickness analysis result (right).

If we now move different balls with diameters within a user defined range through the data set we will find all the different areas with different wall-thicknesses within this user defined thickness range. In an additional step we have to make sure that we do not localize all the corners of the object under investigation since a ball with any diameter will always fit into an edge.

The areas finally localized and classified as relevant are displayed in a report tool providing the user with information, e.g. about the positions and size of the individual areas of minor wall-thickness. The local wall thickness is also displayed colored according to the local wall-thickness. All the information can be easily printed or used to generate a report.

COORDINATE MEASUREMENT AND ACTUAL/NOMINAL COMPARISON WITH CT-DATA:

Although CT is not certified as measurement equipment yet, it is used more and more often as a measurement device. CT has, compared to any other imaging technique, several unbeatable advantages. A CT scan results in a data set with a density of measurement points that is much higher than with any other scanning method e.g. optical or tactile methods. In addition CT provides information about the total objects geometry. Internal geometries that can't be accessed by any other method without destroying the object under investigation can be accessed easily by a CT scan. There are of course still several challenges to solve, e.g. for objects containing different materials with highly differing x-ray absorption coefficients, e.g. objects containing plastics and steel. In such cases the contrast between the materials is often too high to get reasonable geometry measures. However for many applications in the industry CT is an excellent 3D imaging technique, and so voxel data is already used today for geometry analysis, e.g. for actual/nominal comparison tasks in first article inspections. But the processes used today to perform such an analysis task are rather complicated and time consuming. Today the process-chain typically looks as follows: A CT-scan results in a voxel data set which is a stack of grey scale images. The surface of the object under investigation is represented in the CT image stack by the grey value transition between air and material. This surface, defined by a so called iso-grey-value-surface – a surface defined by a specific grey value in space, is extracted as a point cloud or a polygonal mesh and exported, e.g. as a STL file. Due to the large amount of data the polygonal mesh representing the objects surface consist in most cases of too many triangles, so that none of today's actual/nominal comparison software tools is able to handle these polygon meshes. Therefore the polygon mesh has to be "optimized", which means that the number of triangles has to be decimated. The user has to allow a certain tolerance to enable the software tools to successfully reduce the number of triangles.

After all the data processing the geometry measurement or an actual/nominal comparison is finally performed in classical polygon data based software tools. However the decimation process already destroys one advantage of CT data – its extremely high density of measurement points. By decimating the number of triangles in the extracted polygonal mesh we just reduce the number of measured samples.

The question is why somebody converts voxel data into polygonal data and even worse why does he reduce the data's quality by reducing the level of detail by so called mesh optimization? There is no benefit in generating additional intermediate point cloud or triangle data structures.

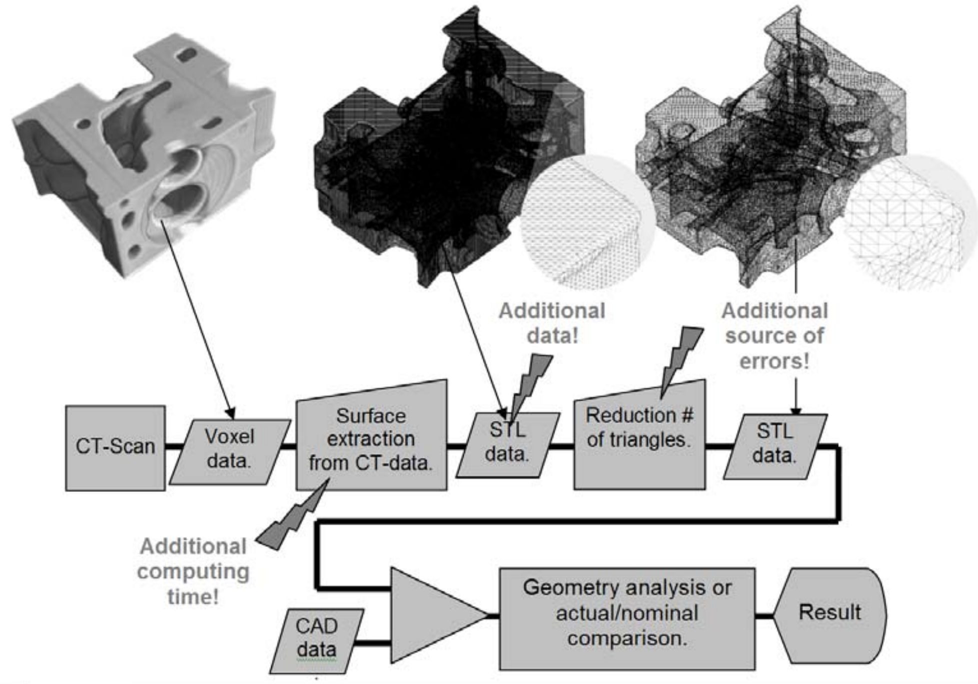

Figure 5, Today's geometry analysis and actual/nominal comparison process chain.

So we asked the question why we should take the detour via polygonal data when we perform a geometry analysis task on industrial CT voxel data? The simple answer is that there was no software tool on the market which is able to handle voxel data directly. Today's software tools have been developed to handle only point clouds or polygon meshes. Therefore everything has to be converted into a point cloud or a polygon mesh.

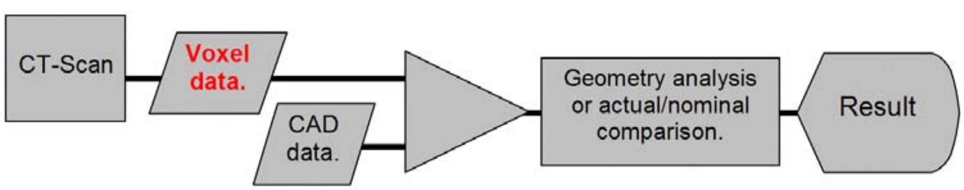

Figure 6, New geometry analysis and actual/nominal comparison process chain.

In the past few months Volume Graphics has developed a voxel data based geometry analysis software and we are in process to release an actual/nominal comparison tool as well capable to work directly on voxel data. The new measurement tool included in our VGStudio MAX application software can be used like a virtual coordinate measurement machine (CMM). The user is able to manually sample a voxel data sets surface to fit simple geometrical primitives, e.g. cylinders, planes, spheres cones and simple points in the data set.

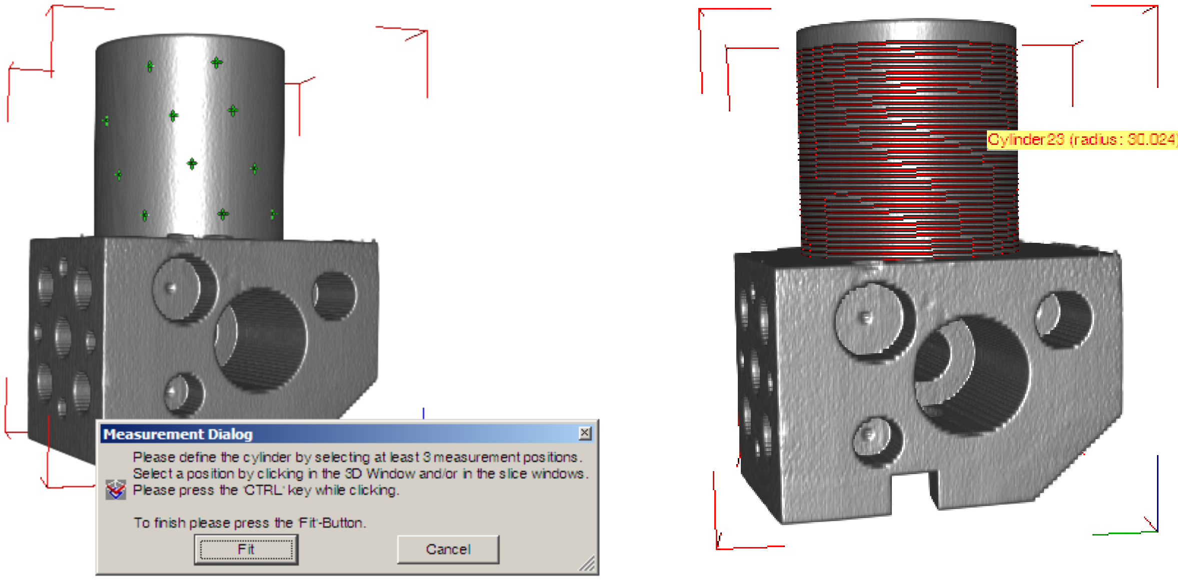

Figure 7, Data set with manually fitted points (left) and fitted cylinder geometry (right)

The primitives themselves or any combination of two primitives can be used to perform a geometrical measurement, e.g. the diameter of a cylinder, or the distance in between two bore holes can be determined. The measurement process is performed by the same methods and guidelines as they are defined for tactile CMMs. The measurement accuracy that can be achieved with the new measurement tool is by far better than the voxel size itself. Sub-voxel-accuracy up to 1/10 of a voxels size can be achieved with highest quality CT data.

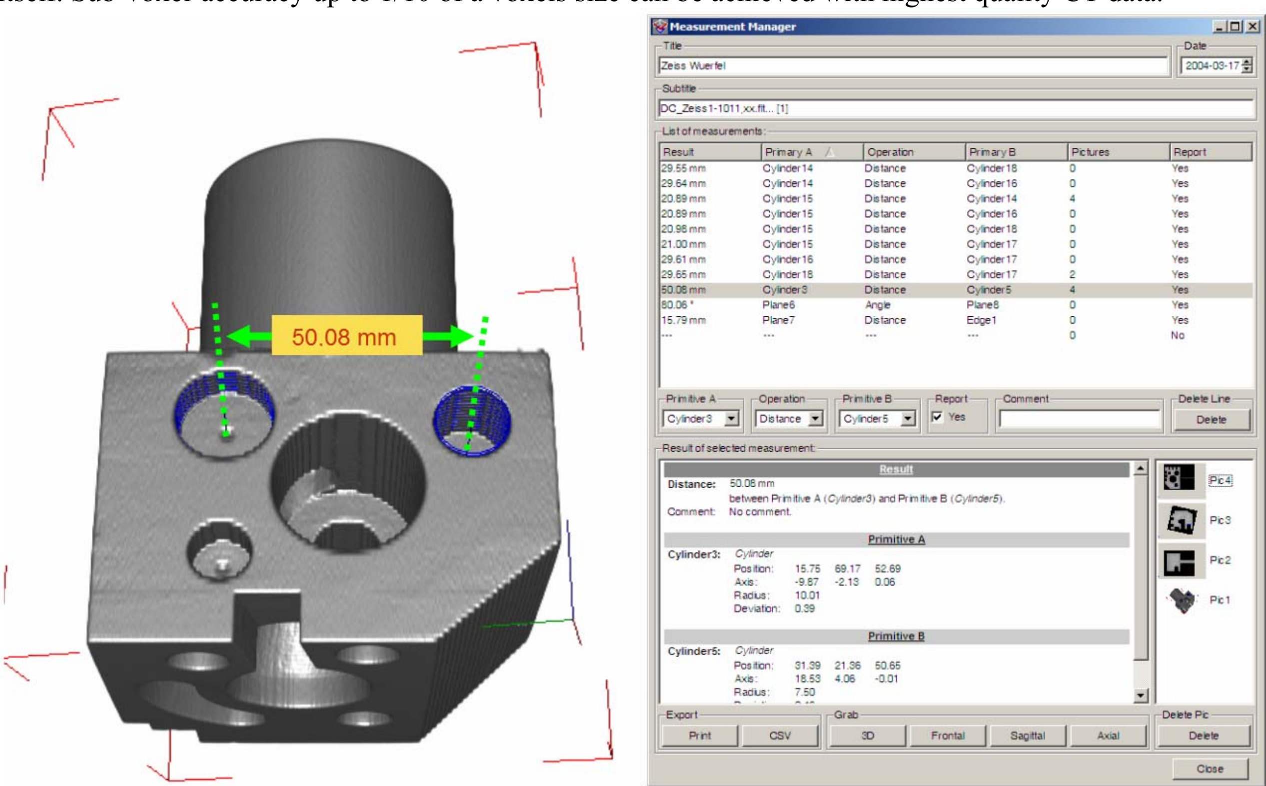

Figure 8, Measurement report generator interface with a distance measurement between two bore holes.

The new actual/nominal comparison tool working directly on voxel data is able to provide its users the maximum level of detail included in their CT data sets. No intermediate data structure like an STL polygon mesh is necessary any longer. The CT data can be compared with the CAD data immediately with highest accuracy. This new software tool will enormously accelerate applications like first article inspection in the casting industry.

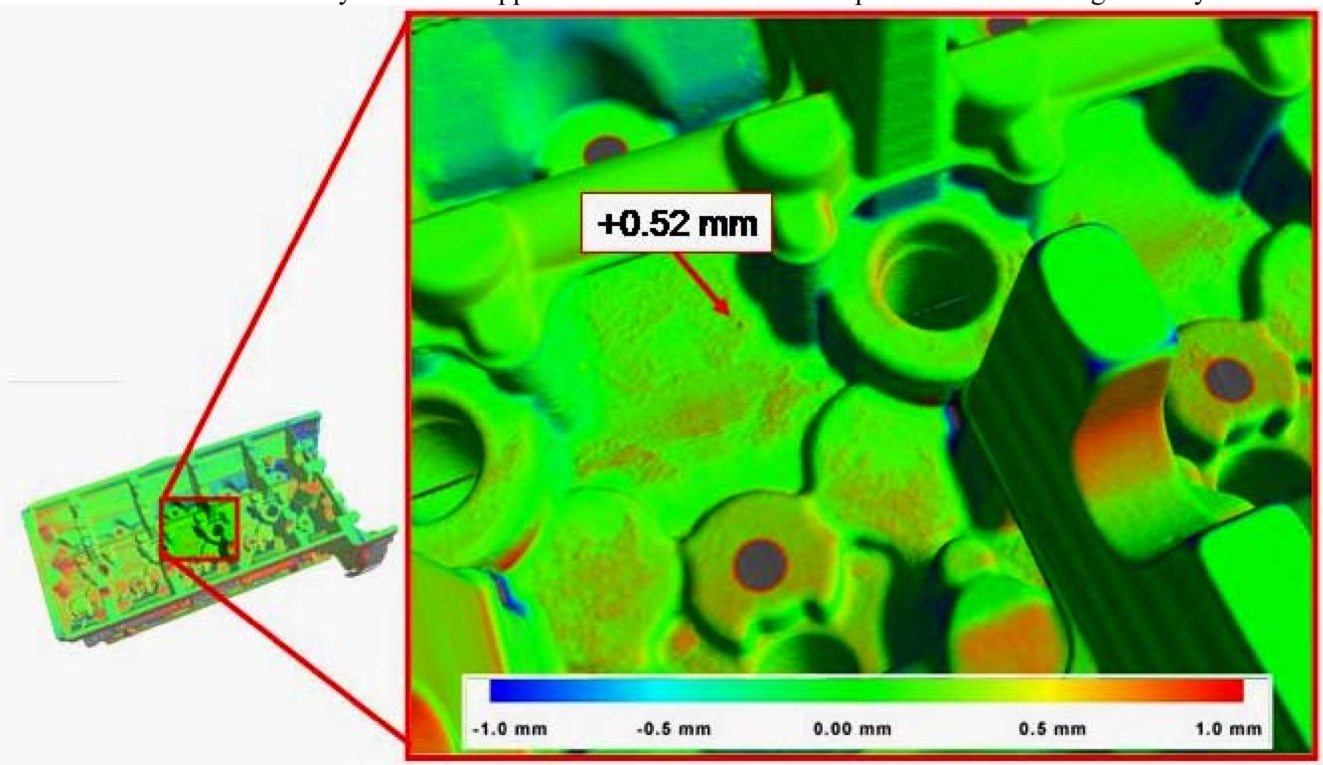

Figure 9, Actual/nominal comparison result based on an industrial CT voxel data set of an engine head.

Conclusions: With a growing number of users, the CT market becomes more and more interesting for the CT manufacturer and software industries. For sure CT-systems will become enhanced, e.g. by better, faster and higher resolution detectors and better x-ray sources, and therefore we will get even more data in shorter scanning time. The growing need for detailed 3D inspection of more complex parts and therefore the growing number of industrial CT users has generated a market for CT data analysis software tools. To satisfy this markets requirements, we continuously develop new software tools like the upcoming voxel based coordinate measurement and actual/nominal comparison tool, and we continuously enhance our application software. But the question still might be: Will we be able to process these huge amounts of data and will we be able to do it in reasonable time? The clear answer is: yes. Already today, 64 bit hardware is available and since the year 2000 our software is available for this platform. Today our customers utilize 64 bit Intel® Itanium or AMD® Opteron multi-processor systems with 16 GByte RAM or more to process data sets with 1024 images with 2048x2048 pixels, this means 8 GByte of data. So we have already pushed the limit one step further. Users have and will always push their applications to the limits of the currently available PC hard- and software and there is no significant limitation for CT users visible at this moment except their financial budget.