3D COMPUTED TOMOGRAPHY - TECHNOLOGY, APPLICATIONS AND PROCESS INTEGRATION

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Abstract: In many sectors of the industry geometric inspection of complex parts is currently solved by conventional measuring procedures using Coordinate Measuring Machines (CMM). This process is very time-consuming and expensive. In many cases a CMM can only be used with great disadvantages compared to non tactile technologies. Internal geometries of complex parts can only be digitised after the object is cut, which automatically leads to losses in the data and difficulties in post-processing, e.g. the alignment of different data-sets. Furthermore it results in a destroyed part, which is often not wanted, especially in the prototype-state of the product development chain.
The huge number of parts, like engine-blocks, cylinder-heads which all have complex outer and inner geometry, and the increasing competition on the global market force the industry to find faster and cheaper methods to bring their products to the market. In the last few years, industry, in particular automotive industry and their suppliers, became more and more familiar with the computed tomography technology (CT). The problem which appeared, was to build-up new process-chains or better, integrate this new technology into existing workflow. The paper will discuss a way to integrate CT for measurement and quality inspection in the existing process chain and show how it worked in industrial applications like flow investigations.

Introduction: Rapid Product Development is one of the main issues in industry. Especially in the automotive and consumer product industry, the focus is definitely on reducing time and costs within the product development chain.

Rapid Prototyping has become a common tool to get prototypes of complex parts fast and meanwhile also cheap. The functionality of those prototypes has not been satisfying, but for mock-up purpose and "just-to-get-a-feeling" of a new developed part, rapid prototyping has been a great solution. Based on that, and also major improvement in material components for RP technologies, Rapid Tooling has become more and more important. Today, Rapid Tooling Technologies are implemented in a large variety of process chains in automotive and other industries. Today we are talking about Rapid Manufacturing. Complex parts, build on Rapid Prototyping machines with new Rapid Prototyping materials for the use as serial parts.

To provide a complete solution for the Product Development Process Chain, it was necessary to improve also the measurement and scanning methods to provide more detailed data within a shorter time. Therefor Computer Tomography was tested and implemented for industrial purpose. Derived from medical applications, software tools have been developed to process the large amount of data, to enable users to modify STL data directly, to measure within the scanned pointcloud and to compare CAD-models with pointclouds of scanned objects.

Results: Speaking of dedication of CT in industry usually means the use of a X-Ray Computer Tomograph. The schematic set-up of a 2D X-Ray CT is shown in Figure 1. Figure 2 shows the inside of a real 3D-CT with its main parts. They can be described as follows: 1) The x-ray source. The power rating vary between 160 keV and 450 keV depending of the object which has to be scanned. 2) The rotation table or manipulator where the object is placed during the scanning process. 3) The detector, where the intensities of the x-rays after crossing the object are measured. There are two types of detectors. Line detectors, which can only record slice by slice (2D) of an object. Array detectors with their matrix-like structure can record a 3 dimensional image of an object. This image is called a 3D-voxelmodel.

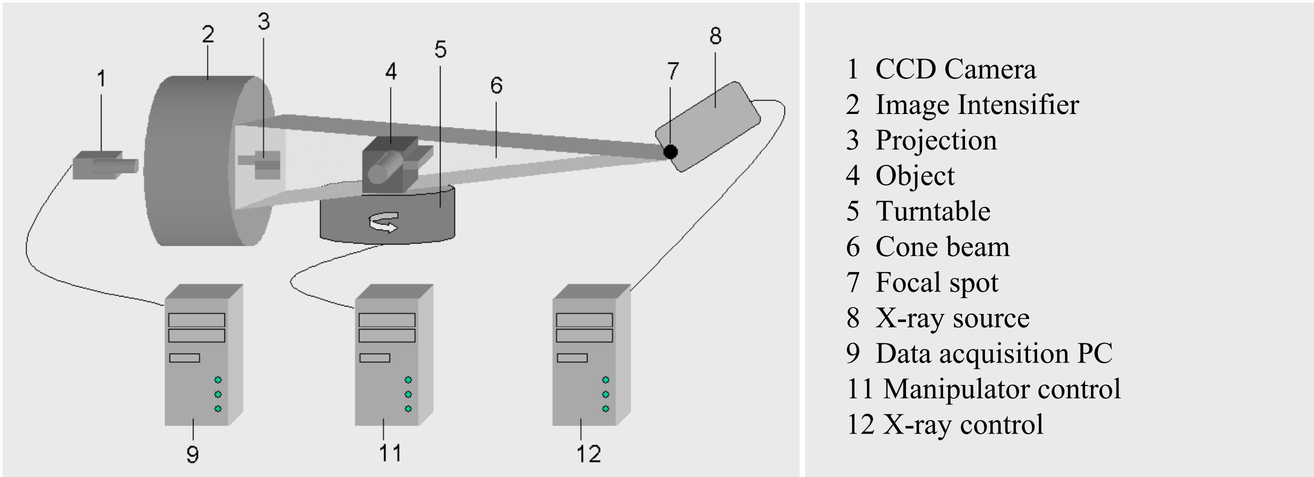

Figure 1: Schematic structure of a 3D CT

Usually in industry like in automotive industry, where computer tomography is mainly used, massive parts with comparatively big wallthicknesses have to be scanned. To pervade the material, high x-ray energy is necessary. On the other hand CT is utilized in plastics industry for small parts with thin walls. High accuracy is demanded. This can be reached by using a micro-focus X-Ray tube. These tubes operate within an energy range of 140 to 225 keV. Fraunhofer IPA uses an industrial CT scanner manufactured by X-Tek Systems Ltd., Great Britain. The system (figure 2 right) is equipped with an 225 kV micro-focus X-ray source, an image intensifier and an 1024 x 1024 Pixel CCD camera. Volumes of 1024^3 voxels can be reconstructed. Measurement time depends on the number of projections and frames (e.g. 20 minutes for 360 projections and 32 frames). The reconstruction works simultaneously and ends right after the data acquisition process is finished. To visualize the resulting voxel model, different software modules are used: VGStudioMAX 1.2, VolumeGraphics, Germany, and MIMICS 8.01, Materialise N.V., Belgium. Both software packages provide segmentation algorithms and surface extraction routines using global threshold values. IPA also uses one of their own software products for the advanced segmentation of CT data for measurement applications. This software provides different local adaptive threshold algorithms and a special voxel-analysis and -correction method, considering material properties and the geometry of the part.

Figure 2: Inside of 3D Micro X-ray CT

The measured intensities in a X-ray projection image provide all of the necessary information to calculate the complete 3 dimensional image of the scanned part. A Fourier Transformation is used to compute the geometrical information based on the intensity values of the x-rays impinging the detector. Figure 3 shows the original aluminium casted part, a projection image, a 3D-voxelmodel and a 2D-slice including errors (lunkers).

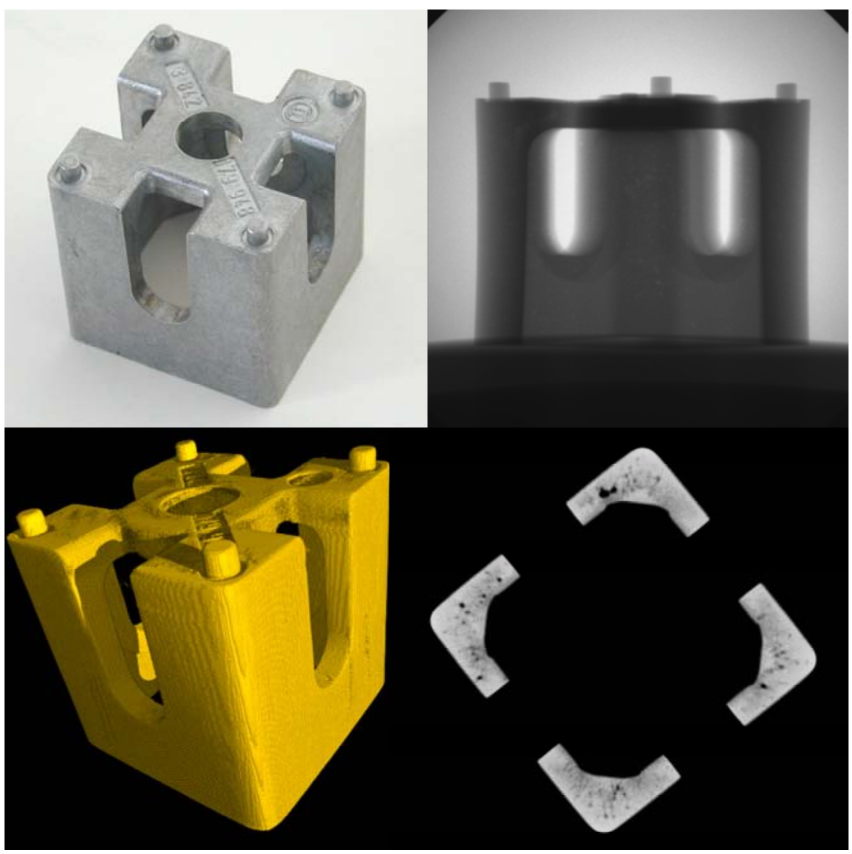

Figure 3: Inside of 3D Micro X-ray CT

There are now two different possibilities to proceed: visualisation or measurement. If visualisation is the goal, the next step is to import the scan-data into a visualisation software tool. One application is the quality control of cast parts. Holes and cracks are vital problems for the casting industry. It becomes now very easy to locate those errors by just browsing through the set of CT grey-value images. There are efforts to automate this process by software and to visualize errors in 3D graphic tools.

The 3D visualization of CT data is done by generating a mesh of triangles, representing the surface of the scanned part. The file format of such a triangulation is called STL and is well known in the world of Rapid Prototyping, as it is the input data format of most of the RP machines.

A little bit more difficult and labour-intensive is the preparation of the scanned data for measurement analysis.

Because of the continuing transition between material and environment in the grey-value images, it is necessary to define a threshold which represents a special grey-value separating material and environment. This segmentation process is not very easy to handle, because of the widely unknown influence of matter and geometry of the scanned object on the threshold value. Fraunhofer IPA and others put a lot of effort in the development of improved threshold algorithms and advanced image processing tools to analyse grey-value images of CT.

After defining a threshold the images/voxel-model is binarised. That means only the colours black and white remain in the image/voxel model. To get the complete inner and outer surface of the object a contour extraction is done. The borderline between the black and white colour is separated (see Figure 4) and the coordinates of those borderline pixels within the image are written in a new file. The result of this, is a 3 dimensional point-cloud representing the surface of the scanned part. This point cloud is the basis for further measurement. Especially developed algorithms to fit geometric features (e.g. lines, planes, circles, ellipses, spheres, cylinders, cones) in 3 dimensional point-clouds provide data like width, height, length and several other measurement categories of interest.

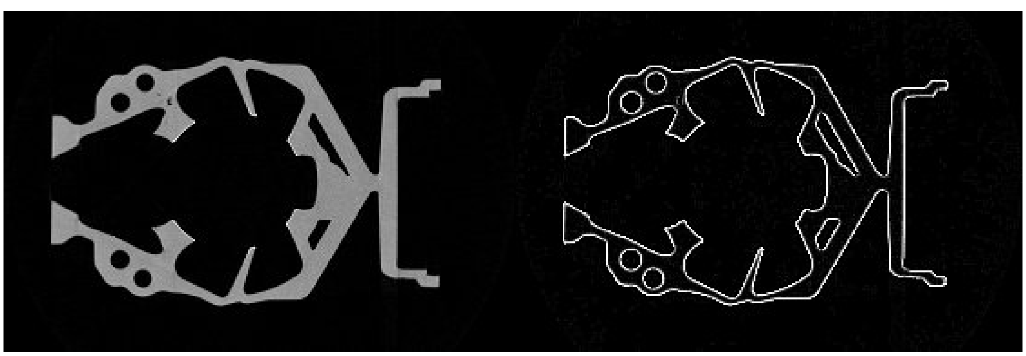

Figure 4: Segmentation process in 2D

Computer Tomographs can not only be used for detecting cracks, blow holes, cavities etc. In series production of e.g. plastic parts it is necessary to check the machine output from time to time to verify the tools accuracy according to the CAD model. This random sampling analysis can be perfectly realised by Computer Tomographs. Figure 5 shows the original part - a plastic impeller – the projection data and the voxel model.

The part was scanned with a voltage of 60 kV and a current of 75 µA. 720 projections have been taken with 64 frames for each projection. The reconstruction parameters were set to a reconstructed volume of 600^3 voxels with a resulting voxel size of about 50µm. The whole scan took about 30 minutes including reconstruction.

The aim of the scan was to obtain a complete scan with all inner geometry of the part. After the segmentation and the surface extraction, the resulting STL file had to be matched with the given

CAD model (IGS format). The software VGStudioMAX 1.2 was used for segmentation and STL generation. Different matching algorithms like 3-2-1, best fit or feature based fits are available. In this example a best fit algorithm has been used after a rough visual matching. Having registered both data sets, the inspection has been run. For both steps, the software Imageware, UGS, U.S.A., has been used.

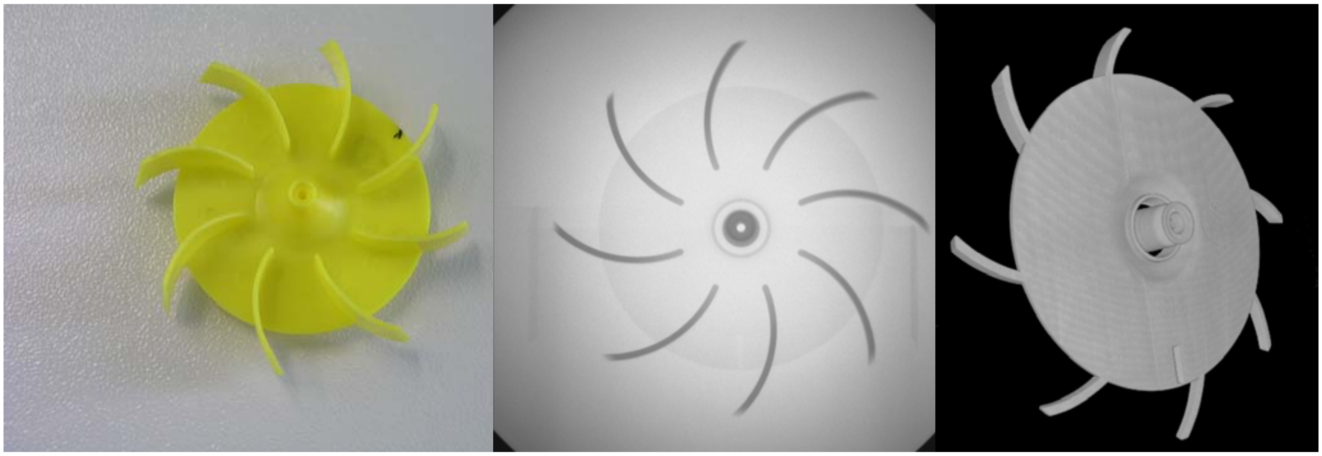

Figure 5: Plastic impeller (l: original part, m: projection image, r: voxel model)

The availability of the voxelmodel enables the user to check the quality of the casting very quickly by browsing through the stack of images or the voxelmodel itself. Furthermore, holes and cracks can be detected and visualized automatically with different software tools. The automated characterization of 3D features in 3D voxelmodels is a very useful tool for quality control especially in aluminium casting industry. After the casting process, there are often a lot more expensive and time-consuming steps, before the product is finished. So, the sooner a crucial error could be detected within the process chain, the less money is wasted.

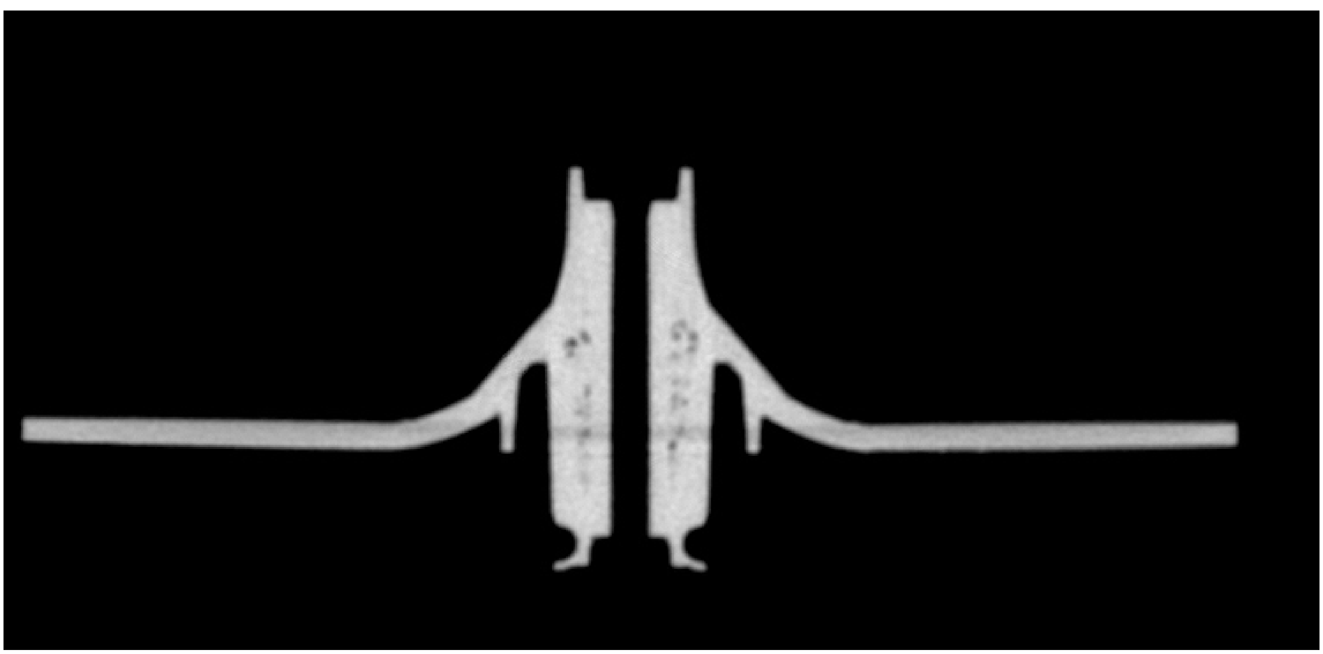

Figure 6: Slice through plastic impeller voxelmodel

CT data obviously provide much more information, than just defects. Geometrical information of outer and inner geometry is available. This is independent of the complexity of the parts and therefore this is a huge advantage compared to conventional scanning methods like laser scanning, fringe projection and tactile measurement. CT measurement is based on three dimensional data processing using complex segmentation algorithms and measurement routines. In order to provide user friendly, fast and accurate tools, a lot of research has been undertaken in this area.

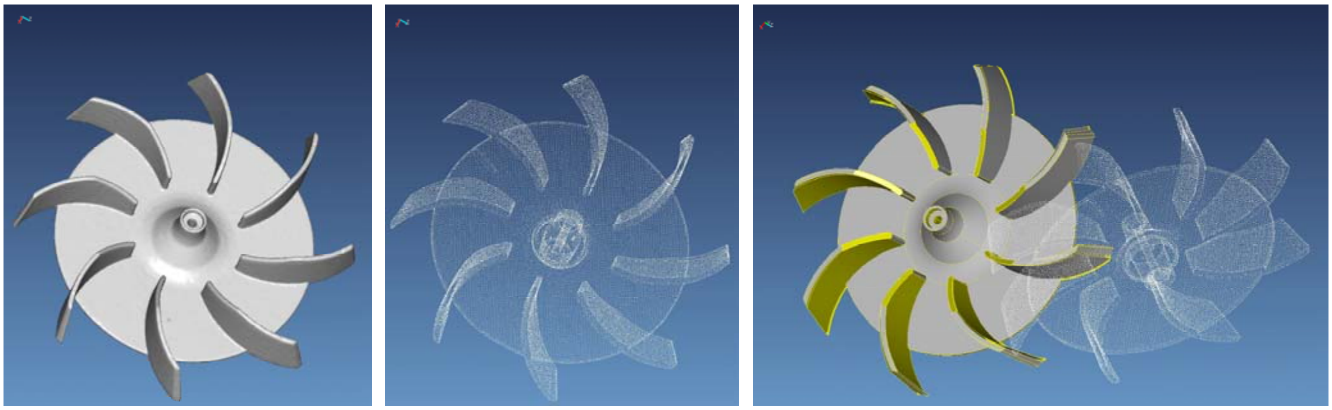

Figure 7: Plastic impeller (l: STL, m: pointcloud, r: unregistered)

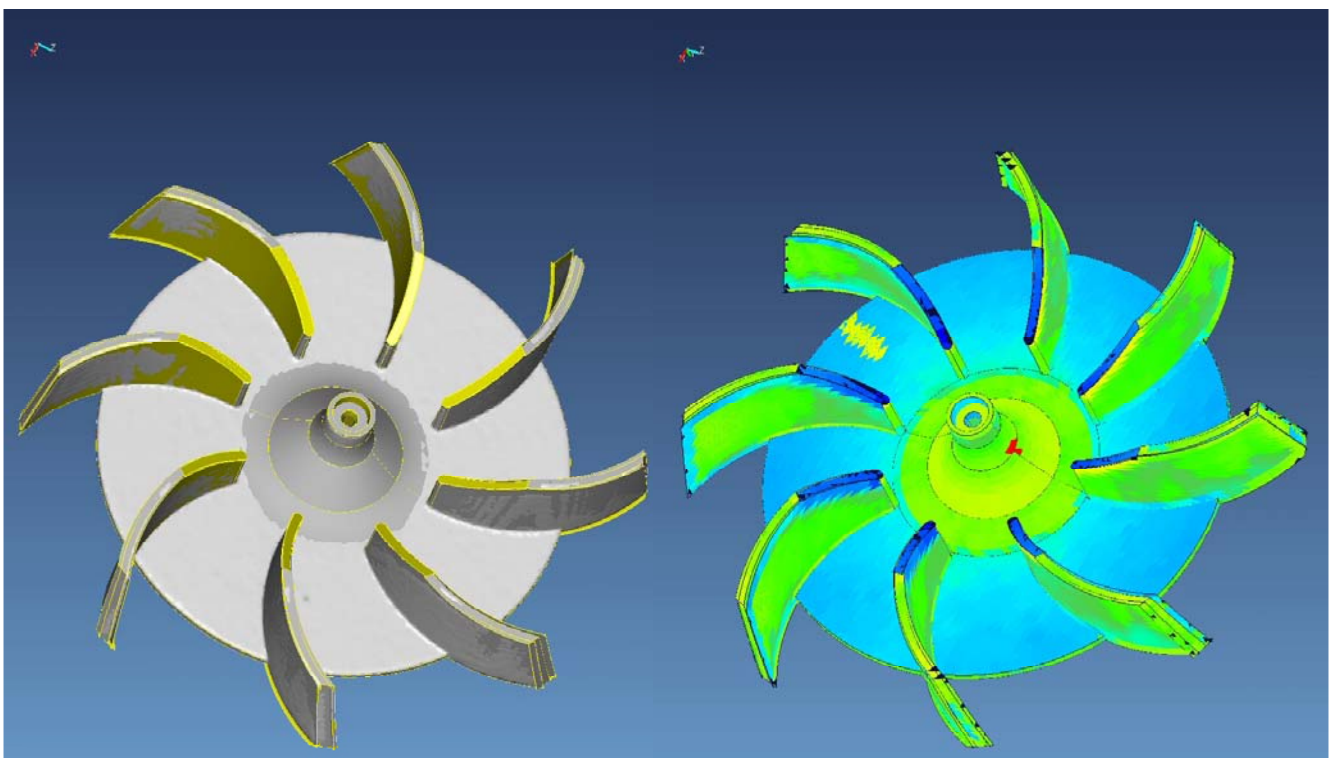

Figure 8: Plastic impeller (l: registered, r: inspection colour plot)

Figure 8 shows CAD model and pointcloud after the alignment is finished. On the right side of the image, the result of a nominal/actual value comparison is shown. The deviations of the point cloud to the CAD-model is displayed with a colour map. Those images can now be used for an inspection report. With today's software it is possible to create almost every report design, whatever is needed in the pursuant company. Details can be shown and points of interests can be listed with their deviations and other statistical information (e.g. min, max and average deviation, standard deviation, number of points in/out of tolerance, etc.). To have not only the colour plot, but also the lists of numbers, that means point co-ordinates with deviation, is a very important criteria for most of the companies.

Discussion: The CT measurement process provides, compared to conventional measurement methods, much more data. Data files with a size of 2 Gigabytes are common. Handling such a huge amount of data is still a problem with today's computers, in spite of the fast developing semiconductor technology. In addition to faster CPUs and more addressable RAM in the hardware components, better software has to be developed, which provides fast and effective tools for intelligent and information-keeping data reduction.

Physical limitations in resolution, x-ray power and the material dependent quality of the results of a CT scan restrict the use of Computer Tomographs in industry. Today it is difficult to gather acceptable results from CT scans of objects consisting of multiple materials. There is a lot of work to do – in software and hardware development – to increase the ability to separate two different materials and to avoid beam hardening and artefacts in the CT grey value images.

Last but not least, it is inevitable to find a standardisation of the whole CT scan process chain, comparable with the ISO standardisation for Co-ordinate measurement machines (CMM) or the VDI/VDE 2617. Two problems to reach that goal, are the manufacturer depending reconstruction and filtering algorithms which are often inaccessible and unreproducible.

Conclusions: Computer Tomography is a powerful tool to analyse the complete geometry of complex parts of a wide range of different materials. With onward software and hardware development the operational area of CT will extend and the acceptance in the industrial field will grow further.
In the past, Fraunhofer IPA worked together in co-operation with several industrial partners to reach this goal. In the user group "volumescanning" (co-ordination: Fraunhofer IPA; partners: DaimlerChrysler AG, BMW AG, Bombardier Rotax, Siemens AG, Robert Bosch AG, MTU AeroEngineering, Rautenbach Aluminium Guss, Andreas Stihl AG, Porsche AG, John Deere Werke, Mahle Filtersysteme) efforts are undertaken to work out standardised inspection reports.
The partners of the European Community project "DETECT" (co-ordination: Fraunhofer IPA; partners: Wälischmiller (GER), Metris n.V. (BE), Materialise n.V. (BE), Centro Ricerche Fiat (ITA), Eidgenoessische Materialpruefungsanstalt (SUI), TomoAdour (FRA), University of Bologna (ITA), University of Cluj-Napoca (ROM), Bombardier-Rotax (AUT)) deals with the improvement of high energy (450 kV) CT using new flat panel detector technology.

On the new field of Hybrid Prototyping, Fraunhofer IPA is working together with a consortium of international partners in a European project called IMS RPD 2001. The global framework of Industrial Manufacturing Systems (IMS) enables the European partners to communicate with partners of other projects with similar topics in the whole world (e.g.: Australia, Korea, Japan and Canada). Main objects of IMS RPD 2001 are to improve the quality of rapid prototyping materials for direct functional use of the prototypes. The development of software tools for Rapid Tooling is another issue. With those tools, the user will be enabled to easily check and modify the tool geometry. For future product development processes, the formation of a Virtual Enterprise is a possibility for further reduction of time and cost. The development and definition of tools and rules for such a Virtual Enterprise are another main objective.
The duration of this follow-up project of IMS RPD (1998-2001) is again 3 years. The project has been started in August 2001, co-ordinated by Fraunhofer IPA. Partners are (ARRK Product Development Group, Bombardier Rotax, Danish Technological Institute, IVF Industrial Research

and Development Corporation, Loughborough University, WIBA AB, DaimlerChrysler AG, Materialise N.V., Ensinger TecaRIM).

Now, Rapid Manufacturing is one of the keywords for further research. Quality control of those rapidly manufactured parts plays also an important role. CT might be one of the possible solutions requested by the industry.

References: /KS-88/ Kak, A.C., Slaney, M.: Principles of Computerized Tomographic Imaging, Society for Industrial and Applied Mathematics (SIAM), Philadelphia, 1988

/NA-01/ Natterer, Frank [et al.]: Mathematical Methods in Image Reconstruction, Society for Industrial and Applied Mathematics, Philadelphia 2001

/NA86/ Natterer, Frank: The mathematics of computerized tomography, B.G.Teubner Verlag Stuttgart und John Wiley & Sons Ltd, 1986

/CA-79/ Castleman, Kenneth: Digital Image Processing, Prentice-Hall Internation Inc., London, 1979

/KL-95/ Klette, Reinhard, Zamperoni, Piero: Handbuch der Operatoren für die Bildbearbeitung, 2. überarbeitete und erweiterte Auflage, Vieweg Verlag, Braunschweig,1995

/HA-95/ Haberäcker, Peter: Praxis der digitalen Bildverarbeitung und Mustererkennung, Hanser Verlag, München, Wien 1995

/CA-86/ Canny, John: A Computational Approach to Edge Detection, IEEE Transactions on Pattern Analysis and Machine Intelligence, Vol. PAMI-8, No. 6, November 1986