HOW INDUSTRIAL COMPUTER TOMOGRAPHY ACCELERATES PRODUCT DEVELOPMENT IN THE LIGHT METAL CASTING AND INJECTION MOULDING INDUSTRY.

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Abstract: Over the past decade Computer Tomography (CT) has become a well recognized tool for rapid product development and quality control in a wide area of industries. Enhancements in x-ray source and detector technologies, CT-scanner system design and data analysis software today offer ready to use solutions for most industries' needs. Especially in light metal and plastic part manufacturing where blank shape parts are produced e.g. in injection moulding, CT has become, citing customers: "the main inspection and measurement tool used in the company". Plastic parts and light metal parts typically can be scanned easily on a modern CT scanner. A single scan, generated in minutes, delivers an amount of information no other technology is able to: all the scanned part's geometry as well as the internal material properties and condition.

Volume Graphics is the pioneer in industrial CT data analysis software. For more than a decade Volume Graphics' software has been enabling their customers to analyze their CT data on standard PC hardware. Using real world examples from customers producing injection moulding parts this presentation will answer the following questions:

1. How do customers use their CT scanner in combination with modern software tools as a coordinate measurement system (CMS) and at the same time how do they use it to inspect the material condition, e.g. detect and analyze porosity and inclusions or fibre orientations.
2. What level of measurement uncertainty can be reached using modern CT equipment.
3. How the user is able to ensure the reliability of the measurement results.

The presentation will further show how the use of CT dramatically saves cost in the customer's product development process by reducing the number of tool compensation cycles and cycle time.

Finally we would like to give an outlook on the potential of how close CT hard- and software technology is today to moving out of the typical quality control lab setup into the production environment to become a fully automated quality control tool.

Keywords: CT, Computer Tomography, NDT, coordinate measuring technology, metrology, actual/nominal comparison, porosity analysis, wall thickness analysis, CAD

1. Introduction

For more than a decade industrial CT is used successfully in the industries. This rather young technology has made tremendous progress from the first "EMI scanner" developed in the 1970ies, generating low resolution 80x80 pixels images of the human brain, to the highly precise industrial CT scanners used for applications in metrology in our days.

In the first years of this millennium CT was mainly used in the industries for material inspection and failure analysis. Already during this phase applications related to the scanned object's geometry appeared. Complex aluminum castings, e.g. engine heads were scanned and their actual geometry was compared against the nominal CAD models to ensure the quality of the castings. Even the process at that time was rather complicated - first generating an STL surface mesh from the CT data, then decimating the enormous amount of triangles, then compare the mesh in software tools developed

originally for optical scanning devices against the CAD model - this have been the first day-to-day applications where CT has approved its ability to capture an objects geometry with sufficient precision. Over the past 6 years, efforts that have mainly been driven in Germany by CT and software manufacturers, associations like the VDI and VDA, end users, and federal institutions like the PTB in Brauschweig and BAM in Berlin, have contributed to the broad acceptance in market to use CT as a coordinate measuring system (CMS).
Knowing and not concealing that CT has its limits resulting already from simple physics, e.g. not all materials can be penetrated in a sufficient way by a given x-ray energy, we can say today that CT has become a universal tool in quality control, product development and failure analysis for a large number of manufacturing industries. CT is able to give its user highly precise information about an objects material conditions and its outside and inside geometry within minutes. No other technology can do the same as simple and efficient than CT.
In this presentation we will focus on applications where CT can show off its advantages to a maximum extend: the light metal and plastic part manufacturing industries. The ideal situation for CT in these industries result from three factors:

- The typical materials used are - so to say - "cooperative" with x-ray CT. Light metals and plastics can be penetrated by today's micro-focus x-ray sources energy ranges in a sufficient way.
- The produced objects consist typically out of a single material or very few materials with a similar x-ray density.
- In injection moulded plastic parts or light metal parts are often blank shape parts requiring no or only in a few areas additional machining. The tolerances for these parts are often not as narrow as for machined surfaces.

The first two factors allow CT to produce highest quality images. An artefact free, low noise, high quality image is the basis for optimal data analysis, if its about material conditions or the objects geometry. The third factor allows CT to provide its users a measurement uncertainty which is sufficient for the actual application (see §3).

2. The use of CT in modern product development in the injection moulding industry

The manufacturer of the plastic connector shown in Fig. 1 produces a large variety of plastic parts and components by injection moulding mainly for the automobile industry.

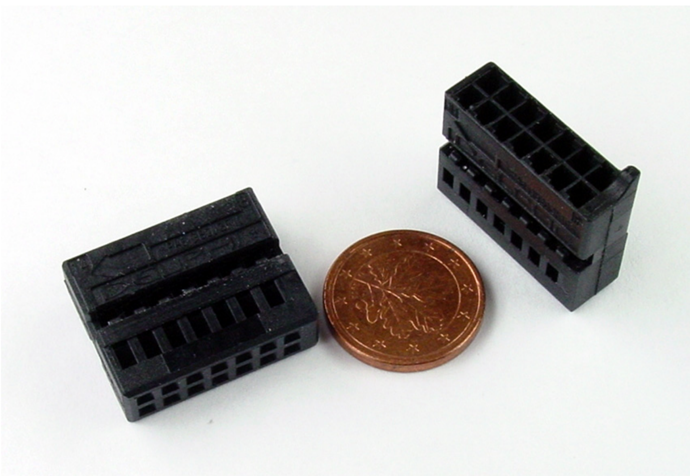

Fig. 1. Injection moulded plastic connector with 14 pins.

The shown connector with 14 pins is produced in a mould with four cavities. Even the part looks simply to a layman the number of features to be measured in a first article inspection is enormous, in total 684 features per cavity have to be measured according to the drawing (Fig. 2)

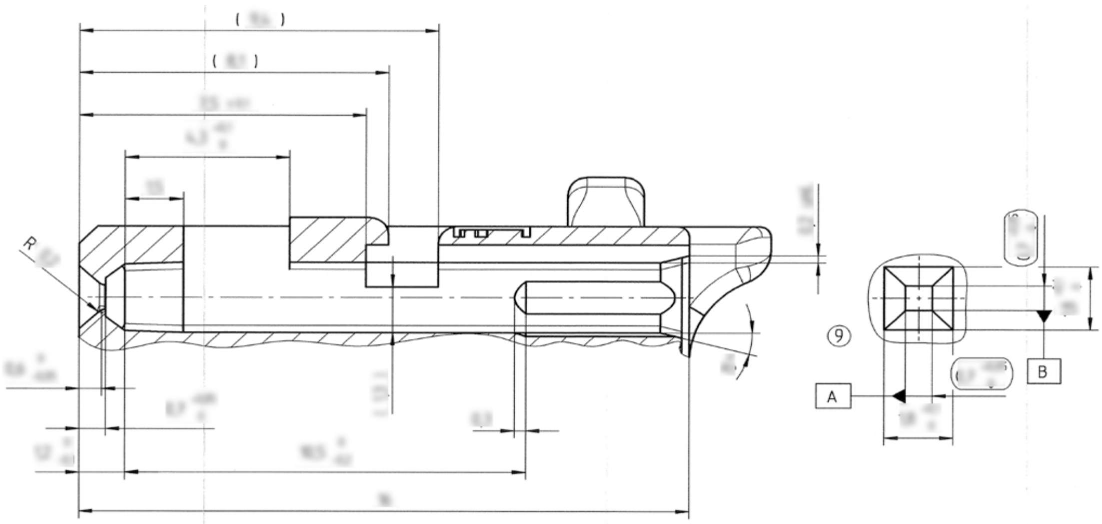

Fig. 2. Detail of the drawing of the 14 pins connector (measures blurred).

This means for a complete first article inspection (FAI) on the four cavities tool 2736 features have to be measured. Before the manufacturer introduced CT in his product development process he used traditional methods cutting and polishing parts to finally measure them with tactile but mainly with optical coordinate measurement systems. To measure the four parts produced in the mould the quality control lab had to cut and prepare dozens of parts to access all features. According to the manufacturer this process took 75 man hours before they could send the resulting report of the FAI back to the tool shop where the mould was revised according to the inspections results.
Several years ago the manufacturer introduced the first 225 keV micro-focus CT scanner in their quality control department. At that time CT had not the wide acceptance it has reached today so that an internal gage repeatability and reproducibility (Gage R&R) study was performed. It successfully approved that the CT scanner and the established procedures ensuring the correct operation of the scanner fulfilled the companies requirements for a CMS used in product development. Over the years the tools used have been refined especially the software. Today the customer uses VGStudio MAX 2.1 for coordinate measuring, nominal/actual comparison and porosity analysis tasks. The software is working directly on the voxel data generated by the CT scanner so that there is no need anymore to generate a polygonal surface mesh from the slice image data. This eliminates additional sources of error in the process chain and therefore improves the achievable measurement uncertainty. At the same time it reduces the processing time.
Today the part is scanned, typically in less than 30 minutes, the data is imported in the software and a measurement template is programmed on the actual data set. In most cases the programming of the measurement template can even be performed in advance before the actual CT data set is available on the CAD model in VGStudio MAX. In this case once the scan is finished the measurement template generated on the CAD model can immediately be used to measure the actual part.

Using CT and dedicated CT data analysis software like VGStudio MAX now accelerates the companies FAI process in their day to day work dramatically. There is no longer the need to cut and polish dozens of parts. All measurements can be done on four parts only. Besides the time it takes to scan the parts only the programming of the measurement template and preparing the documentation defines the duration for a FAI.

In case of connectors like shown in this example where the individual pin geometries typically are identical even the programming of the measurement template can be optimized. An experienced user is able to generate a measurement template for one pin according to a drawing like details are shown in Fig. 2, in a less than one hour. The remaining pins can be measured by simply applying the measurement template of the first pin to all remaining pins in a user defined grid pattern. The example shown in Fig. 3 takes on a modern PC only seconds to measure the remaining 13 pins.

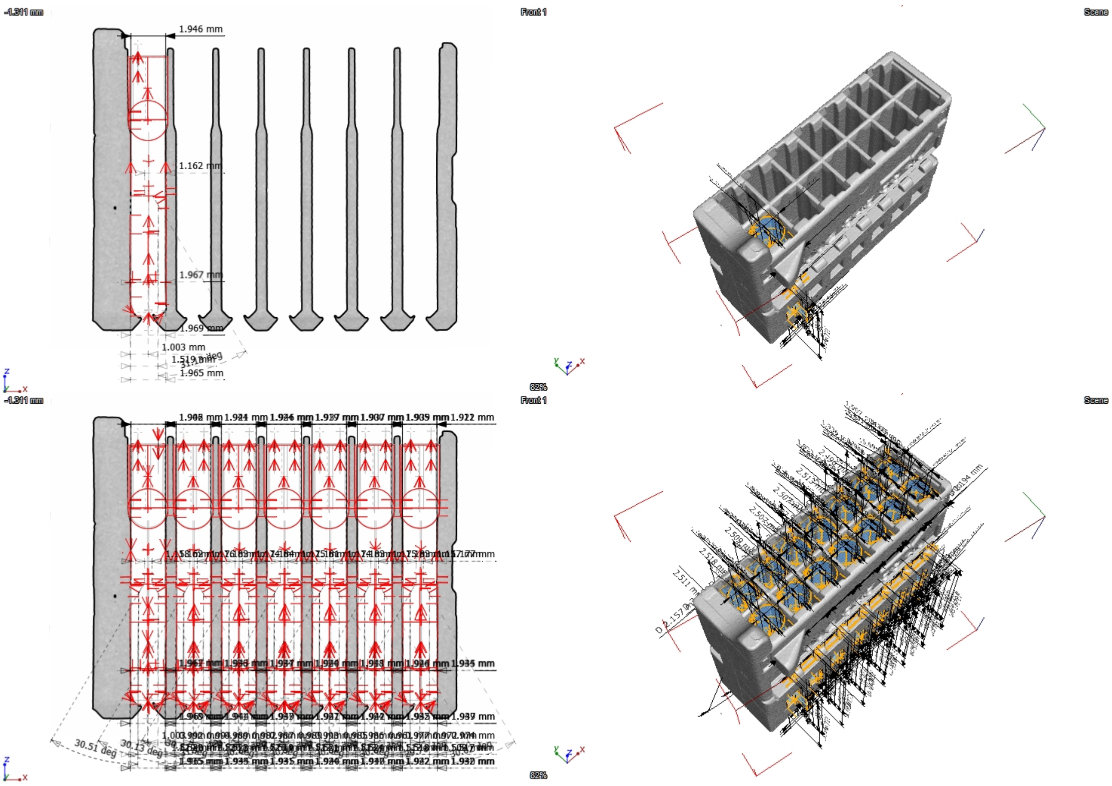

Fig. 3.Applying a pin measurement template by user defined grid patterns.

Once the complete measurement template was generated either on the first part or on the CAD model VGStudio MAX 2.1 offers macro and batch processing. This allows the user to inspect additional data sets in a fully automated way. For moulds with a large number of cavities, e.g. 32, this option saves more and more time. The inspection of a complete series of parts can run at night on the PC after the quality control engineer leaves the office.

In case of the example shown here the duration for the FAI was reduced to less than 16 man hours. Already for a average complex part this is a dramatic improvement of aprox. 80%!

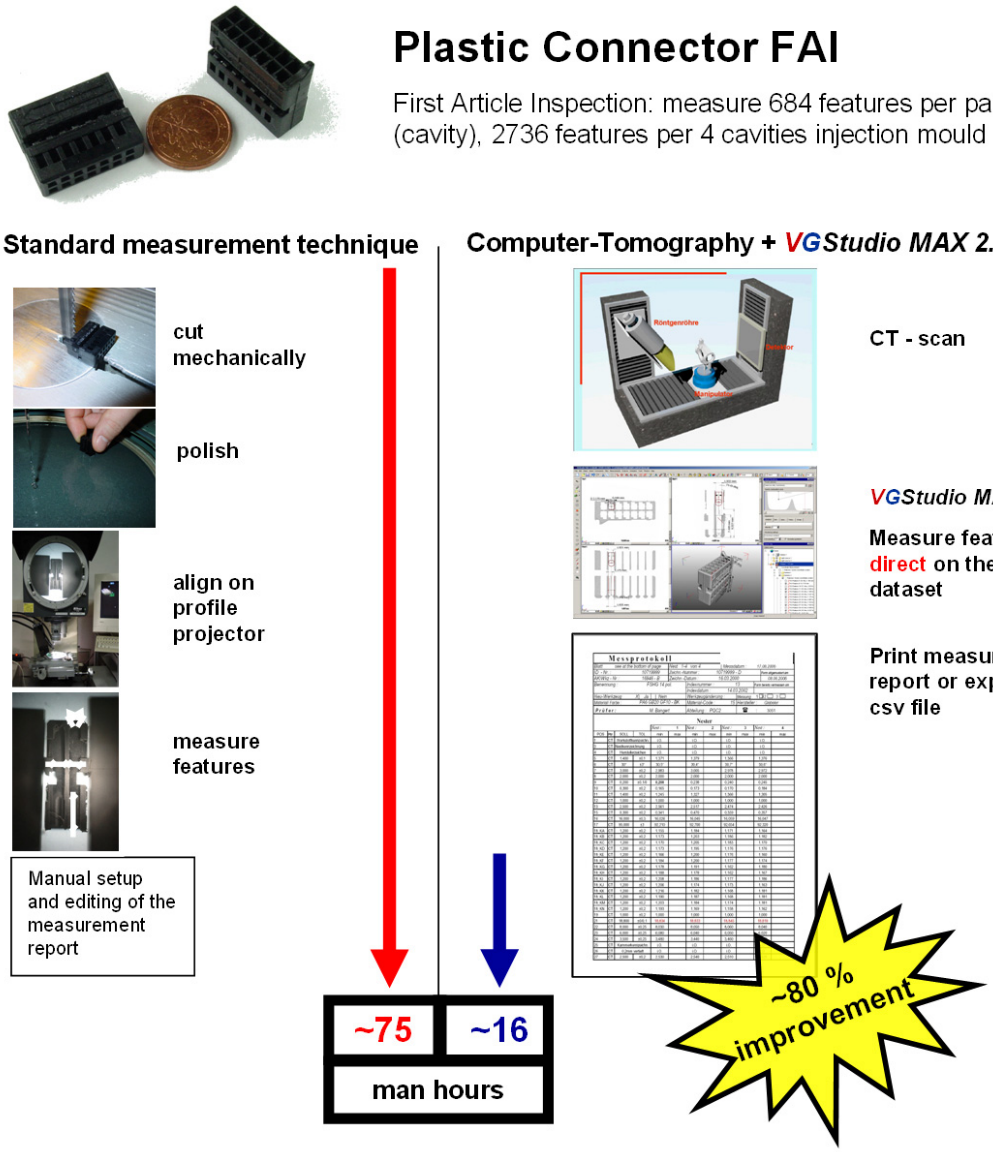

Fig. 4. Time saving in the FAI of a 14 pin plastic connector.

The time and therefore cost saving for the company gained in a single FAI (Fig. 4) so far is already impressive but there are additional aspects improving the balance sheet of the use of CT even more. In an classical product development process the optimization of the mould is an iterative process. Features measured as out of tolerance in the FAI lead to a correction of the mould performed in the tool shop. Once the mould is corrected it gets mounted in the injection moulding machine again and new parts are produced. In the following inspection with classical methods often only those features get measured again which have been identified as out of tolerance in the first iteration cycle. Not measuring all features helped shortening the cycle time, however in many cases it caused that some features measured in tolerance in the previous cycle showed up as out of tolerance in a later causing an additional time consuming and therefore expensive iteration cycle.

Using CT and modern measurement software allows to measure all features in all iteration cycles. Once a connector is scanned in the CT scanner applying the complete measurement template takes only minutes even for large highly complex parts. Therefore the user of CT has in every cycle 100% information not missing any relevant changes in the produced parts' geometry. According to a number of our customers of the use of CT has reduced the number of tool optimization iteration cycles by nearly half. Fig. 5 shows the effect of shortening the FAI time and reducing the number of tool correction iteration cycles on an example of a complex 80 pin connector.

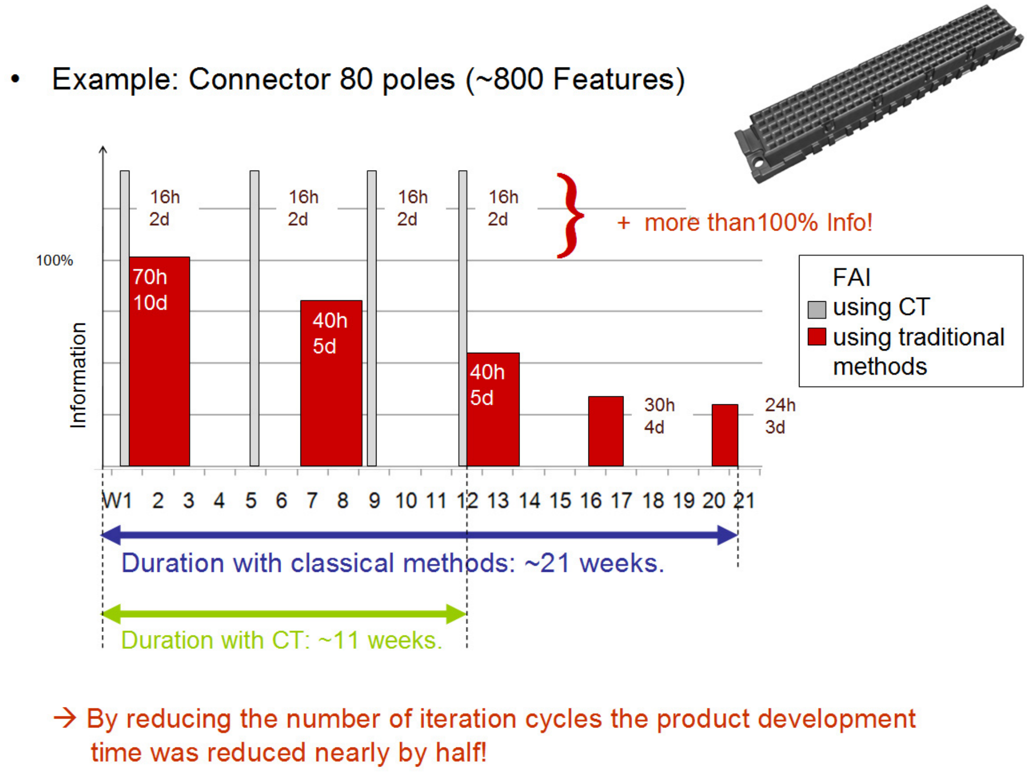

Fig. 5. CT reducing the number of tool optimization iteration cycles.

Besides 100% of information of the parts geometry CT is able to offer even more benefits. The scanned slice images do not only reveal out of tolerance geometries of features defined by the drawing. The same data can be used to perform different analysis tasks like a nominal/actual comparison with the CAD model. The colors encoded view of a data set is able to enhance the understanding of the tool maker how to correct for distortions of the part's geometry.

Another analysis can be an automated wall-thickness analysis revealing in seconds if minimum wall-thicknesses are fallen below somewhere in the part.

Finally CT's traditional application providing information about the material conditions can also be of help to improve the production. An automated inspection for imperfections like inclusions or porosity can be performed on the same data we used for the inspection of the parts geometry.

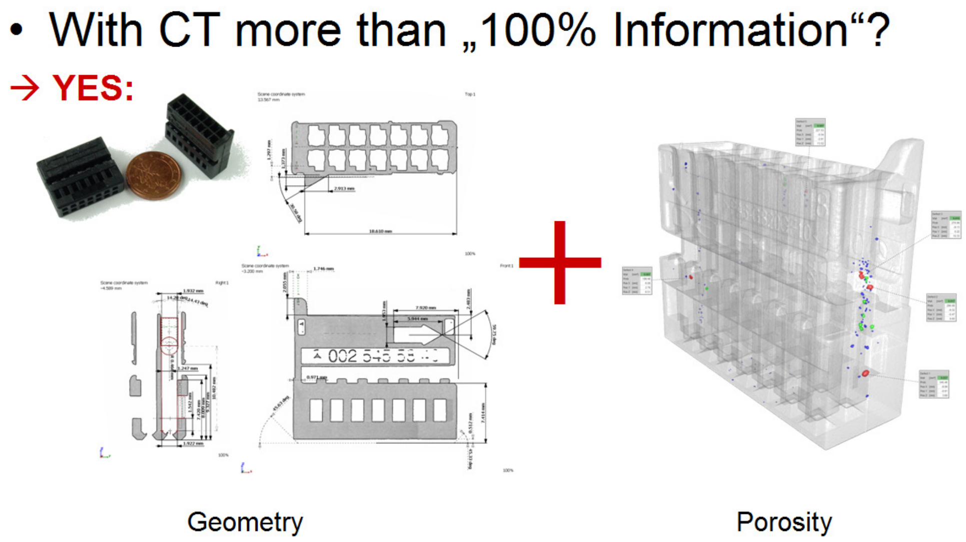

Fig. 6. CT provides information on geometry and material related aspects.

All the different analyzes methods described above can be automated in VGStudio MAX by macro and batch processing. This allows the user to run more significant inspection tasks, taking more that only geometry related aspects into account. All this helps shorten the product development time, offering the manufacturing industries the chance to shorten their time to market. In a world where product life cycle times get shorter and shorter, this is an enormous advantage over competitors not using the same technologies.

3. CT and measurement uncertainty

Today users are able to get a qualified statements on the capabilities of a CT system being used as a CMS. Thanks to the activities under the direction of German institutions like the national metrology laboratory PTB or organizations like the association of German engineers VDI[1] guidelines have been released or are in preparation which define exact procedures e.g. for system acceptance tests. Therefore CT manufacturers are now able to provide reliable and comparable numbers for measurement uncertainties according to the VDI 2630 guideline (Dez. 2009 still draft). You can now find from different manufacturers of micro focus CT scanners declarations about measurement uncertainties like 4,5 µm + L/100 or 9 µm + L/50 for their equipment, where L is the measured length.
CT scanner equipment is in our days from a mechanical point of view more and more often build like traditional CM equipment using similar technologies and temperature stable materials like a granite base or a temperature compensating mechanical setup. In combination with automated build in or semi-automated calibration procedures modern CT equipment becomes as reliable as a classical CMS in day-to-day work.
Users not using the latest CT scanner generation are able to enhance and approve the measurement uncertainty of their scan equipment. The different factors influencing a CT scanners imaging quality and therefore its measurement uncertainty have been under investigation for many years now. Besides a global scaling error two sources of error in the scanners mechanical setup have been observed as having a significant

[1] VDI/VDE-expert committee 3.33, „Computer tomography in dimensional measuring“

influence on the scanners measurement uncertainty[2]. The sources of error are: the horizontal rotation axis shift and the "in-detector-plane" rotation axis tilt These errors can be compensated today with advanced CT reconstruction software. The build in CT reconstruction module of VGStudio MAX offers automated correction of the two geometry errors improving image quality and therefore reducing the systems measurement uncertainty.

The global scaling error can not be corrected automatically from the projection image data yet like in the two cases described above. The scaling error results from a falls scanner geometry influencing the scanners magnification factor resulting from the ratio of Focus-Detector-Distance (FDD) and Focus-Object-Distance (FOD). In our customer base we frequently observe an error in the FDD up to 2%. This is in many cases caused by a non temperature stable environment where the CT scanner is used. The observed errors often fit nicely the temperature caused expansion of the steel base of the scanner.

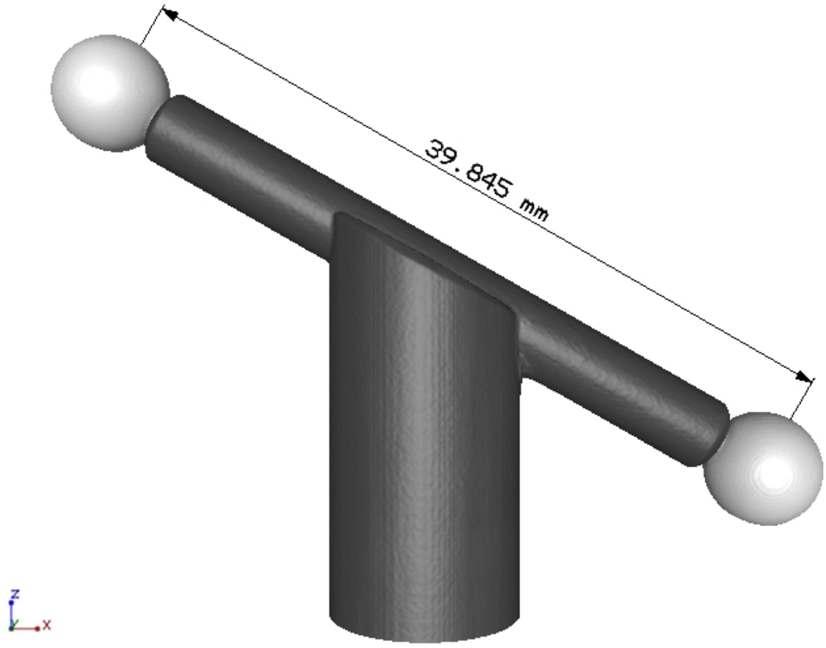

Fig. 7. CT scan of a calibrated phantom consisting of two ruby balls on a carbon fibre rood.

To correct for this kind of error it is best to use a calibration phantom. Several CT manufacturers offer optional test phantoms which have been calibrated by a certified test lab. These phantoms (Fig. 7) often consist of two or more ruby balls mounted, e.g. on carbon rods. Even more complex calibrated phantoms like ball scraper cubes (Fig. 8)[3] can be acquired commercially allowing more complex analysis of the distortion in the scan area by measuring the distances between each ball scraper pair.

The scaling error can be evaluated by scanning the phantom and measuring the sphere center distance between the ruby balls. Comparing the resulting measure with the nominal value will give the user the scaling error. This factor should be used to correct the FDD before the object under investigation is scanned and the CT reconstruction is calculated.

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[2] Examination of the Measurement Uncertainty on Dimensional Measurements by X-ray Computed TomographyS. Kasperl1 , P. Wenig2, ECNDT 2006

[3] http://www.feinmess.com/de/produkte-kalottenwuerfel.html

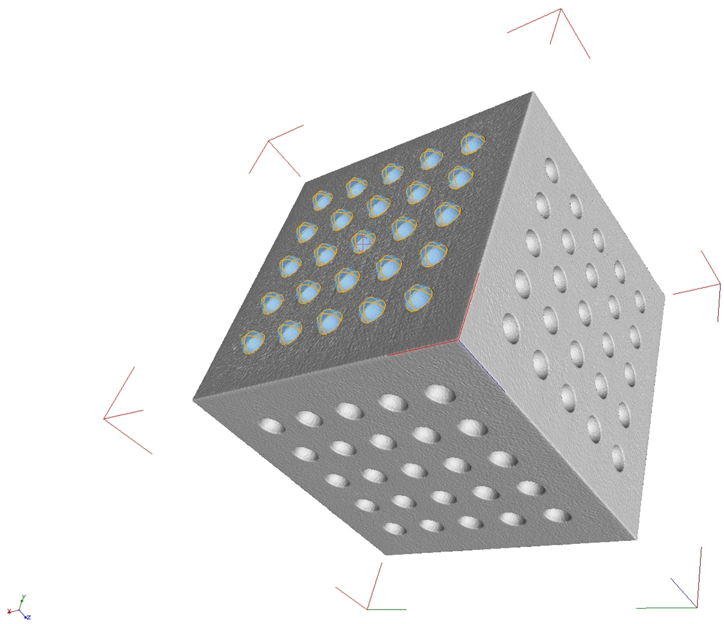

Fig. 8. CT scan of a ball scraper cubes phantom.

Correcting the scaling error after the CT reconstruction by simply scaling the voxel resolution will correct the error partially but not in an optimal way. A CT reconstruction calculated under a falls FDD will cause that the cone beam angle under which the back-projection is performed, is wrong. This will result in minor distortions in the scanned data set. This effect can be observed e.g. by a degradation of the form-factors of regular geometries probed on the CT data, e.g. the form-factors of the ruby balls of the calibration phantoms. The graph in Fig. 9 shows how the form factor of a sphere in a simulated CT data set changes in relation to the form factor under ideal conditions when the scaling error is varied by +/- 10%. A simulated data set was used to ensure that the exact scan geometry is know for this experiment.

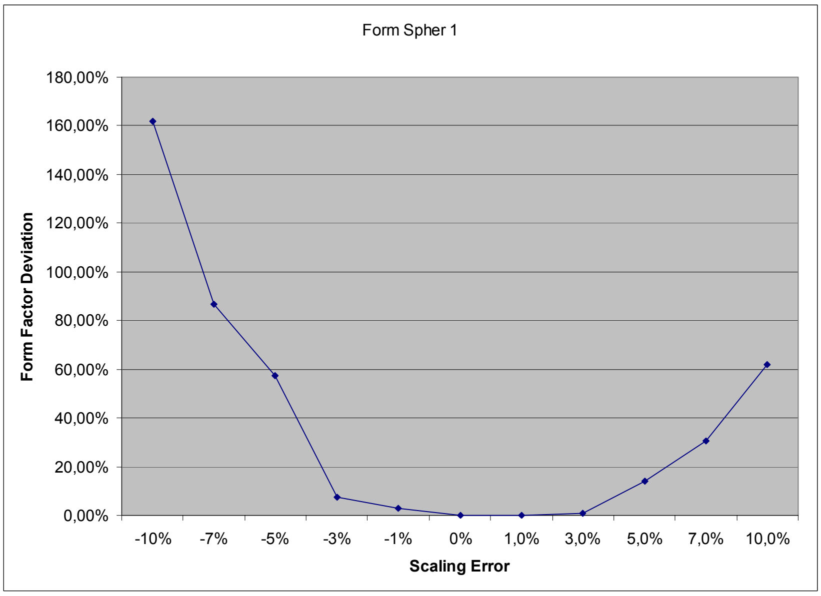

Fig. 9. CT scan of a calibrated phantom consisting of two ruby balls on a carbon fibre rood.

CT users can easily ensure by scanning calibration phantoms on a regular base that their systems is working in correct conditions. By using the phantom before an actual scan to correct for the actual FOD / FDD geometry users can ensure that he reaches the minimum measurement uncertainties. Under optimal conditions users applying the above described procedures have reached measurement uncertainties as small as 1/10 of a voxel and better depending on their application.

4. Outlook

Industrial CT has approved over more than a decade its capabilities in all kind of applications in the quality control lab. Its time and cost saving potential in product development, e.g. in the injection moulding industry have been presented in this paper. However the potential of CT in industrial applications is by far larger.
Up to now only very few CT systems have been installed and used in or close to the production lines. The use of CT in inline inspection has been limited mainly by the data acquisition time or if the acquisition could be performed fast enough by the image quality and the resulting limits in data analysis. In the past few years we have seen developments and improvements in CT hardware and software. The latest X-ray tube generation in medical applications now provide sufficient power to realize scan times fast enough for inline inspection. Their scan resolutions is limited to the range of several tenth of a millimetres. Applications for these kind of tubes might therefore be initially be limited to the inspection of medium sized castings, where first tests have been very promising.

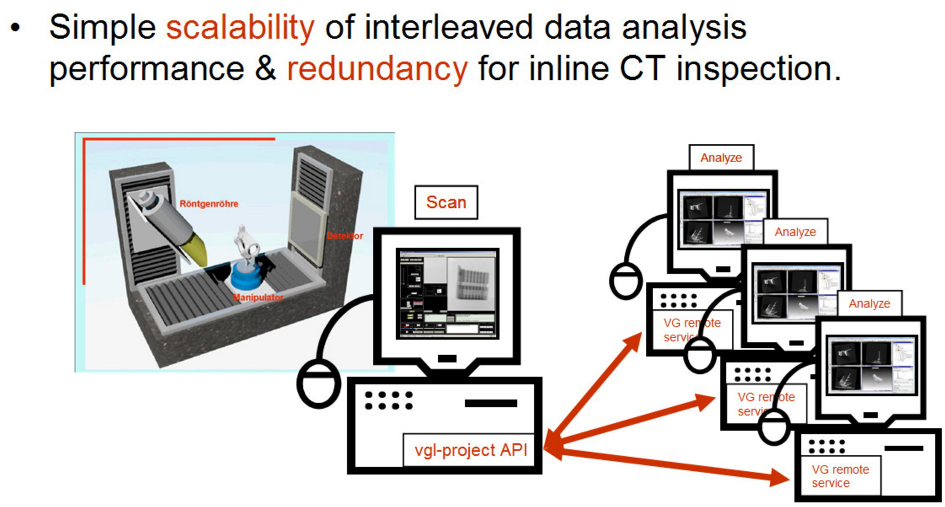

Fig. 10. VGStudio MAX allows to build a scalable, redundant data analysis system for inline inspection.

With our latest developments in CT data analysis software we offer the CT manufacturers and system builders a tool that offers a highly flexible data analysis environment for fully automated material condition related as well as geometry related analysis tasks. The analysis tasks to be performed can easily be defined by recording macros. The data analysis macros can be activated from the CT-scanner's system software on a single or even several remote PCs. This allows to scale the data analysis performance and at the same time to build a fail save redundant data analysis system.
With all these developments in the rapidly growing industrial CT market in mind we are sure that today we only see the tip of the iceberg of industrial CT use in the industries. CT has the potential to become the universal inspection tool of the future.