52. IWK

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FACULTY OF COMPUTER SCIENCE AND AUTOMATION

COMPUTER SCIENCE MEETS AUTOMATION

VOLUME II

Session 6 - Environmental Systems: Management and Optimisation
Session 7 - New Methods and Technologies for Medicine and Biology
Session 8 - Embedded System Design and Application
Session 9 - Image Processing, Image Analysis and Computer Vision
Session 10 - Mobile Communications
Session 11 - Education in Computer Science and Automation

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Preface

Dear Participants,

Confronted with the ever-increasing complexity of technical processes and the growing demands on their efficiency, security and flexibility, the scientific world needs to establish new methods of engineering design and new methods of systems operation. The factors likely to affect the design of the smart systems of the future will doubtless include the following:

- As computational costs decrease, it will be possible to apply more complex algorithms, even in real time. These algorithms will take into account system nonlinearities or provide online optimisation of the system's performance.
- New fields of application will be addressed. Interest is now being expressed, beyond that in "classical" technical systems and processes, in environmental systems or medical and bioengineering applications.
- The boundaries between software and hardware design are being eroded. New design methods will include co-design of software and hardware and even of sensor and actuator components.
- Automation will not only replace human operators but will assist, support and supervise humans so that their work is safe and even more effective.
- Networked systems or swarms will be crucial, requiring improvement of the communication within them and study of how their behaviour can be made globally consistent.
- The issues of security and safety, not only during the operation of systems but also in the course of their design, will continue to increase in importance.

The title "Computer Science meets Automation", borne by the 52nd International Scientific Colloquium (IWK) at the Technische Universität Ilmenau, Germany, expresses the desire of scientists and engineers to rise to these challenges, cooperating closely on innovative methods in the two disciplines of computer science and automation.

The IWK has a long tradition going back as far as 1953. In the years before 1989, a major function of the colloquium was to bring together scientists from both sides of the Iron Curtain. Naturally, bonds were also deepened between the countries from the East. Today, the objective of the colloquium is still to bring researchers together. They come from the eastern and western member states of the European Union, and, indeed, from all over the world. All who wish to share their ideas on the points where "Computer Science meets Automation" are addressed by this colloquium at the Technische Universität Ilmenau.

All the University's Faculties have joined forces to ensure that nothing is left out. Control engineering, information science, cybernetics, communication technology and systems engineering – for all of these and their applications (ranging from biological systems to heavy engineering), the issues are being covered.

Together with all the organizers I should like to thank you for your contributions to the conference, ensuring, as they do, a most interesting colloquium programme of an interdisciplinary nature.
I am looking forward to an inspiring colloquium. It promises to be a fine platform for you to present your research, to address new concepts and to meet colleagues in Ilmenau.

Professor Peter Scharff
Rector, TU Ilmenau

Professor Christoph Ament
Head of Organisation

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52nd Internationales Wissenschaftliches Kolloquium
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Dr. H. Lettenbauer / Dr. D. Weiss

X-ray image acquisition, processing and evaluation for CT-based dimensional metrology

ABSTRACT

X-ray computed tomography (CT) reconstructs an object from X-ray projection images and has long been used for qualitative investigation of internal structures in industrial applications. Recently, cone-beam CT has been adapted to the task of high-precision dimensional metrology of machined parts, providing a method of rapidly acquiring comprehensive and quantitative data on parts of arbitrary complexity.

High-power micro-focus X-ray tubes, large-size flat panel X-ray detectors, very accurate linear and rotary drives and a high-performance reconstruction solution are combined to image and measure a wide spectrum of parts manufactured from polymer and metal alloys according to established metrology standards.

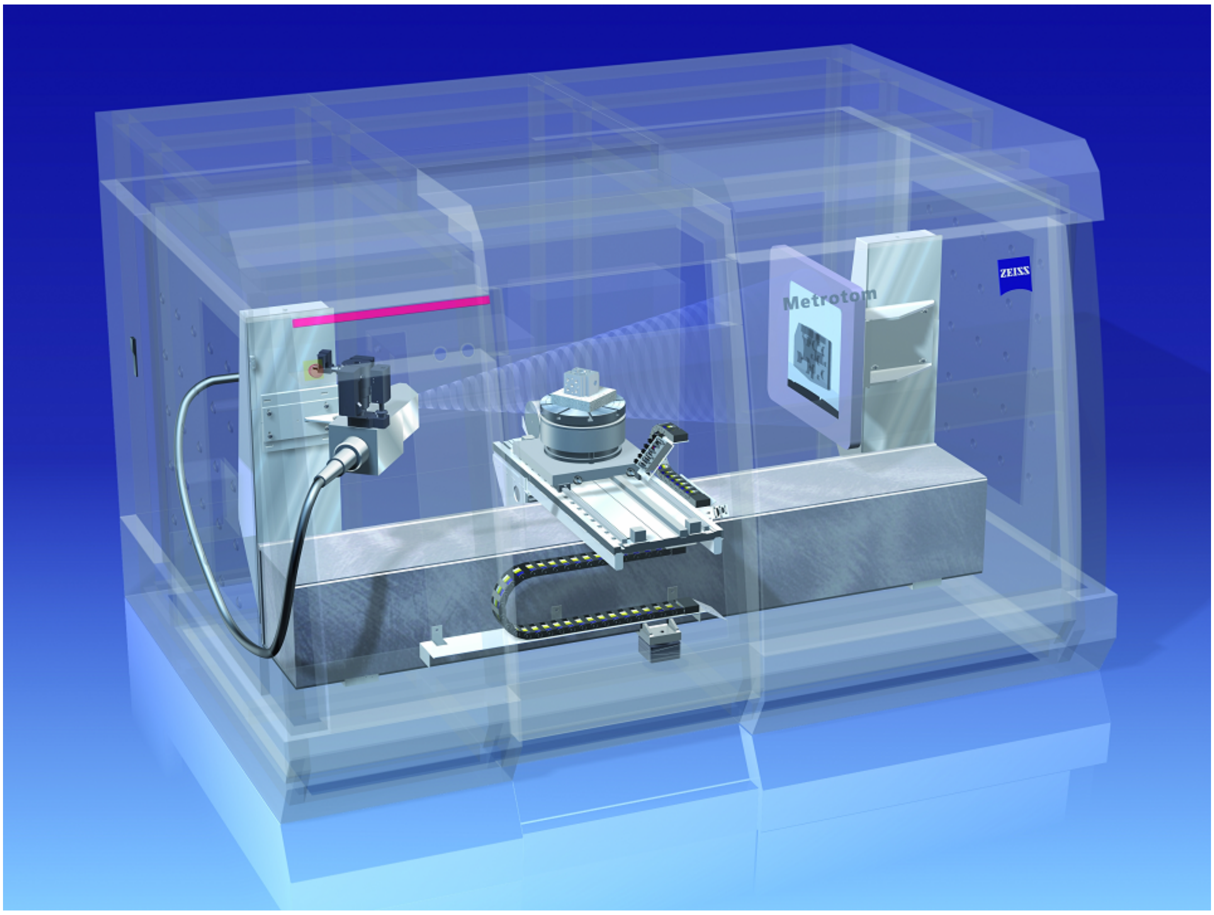
Various calibration techniques are used at the several stages of the measurement process to e.g. characterize the behavior of X-ray tube and detector and precisely define the imaging geometry.

To verify the measurement accuracy, suitable objects such as geometrical elements are calibrated according to international standards and then measured using the CT. Dimensional metrology is performed on the reconstructed objects, either directly or using an intermediate surface-extraction step. The results of these measurements are compared to the reference values of the calibrated objects; the level of agreement of the results defines the accuracy of the CT measurement. Using established methods to define measurement uncertainty ensures a high level of acceptance with dimensional metrology users.

INTRODUCTION

From an image-processing point of view, computed tomography is based on exploiting the known geometrical configuration of source, object and detector to obtain a numerical representation of the object. For cone-beam X-ray CT, image formation is based on a perspective projection of the object density (which is encoded as X-ray intensity). For metrology purposes, the resulting object representation needs to reproduce the object surface with an accuracy that is much better than the voxel resolution. This accuracy cannot be assessed from the volumetric data with the naked eye. It is in this regard of quantitative evaluation with sub-voxel precision that metrology-capable computer tomographs differ most importantly from their predecessors that were aimed at non-destructive testing (NDT) and a mostly qualitative evaluation of volumetric data.

COMPONENTS



A metrology-enabled computer tomograph such as the METROTOM (Carl Zeiss) employs the same components as a classical NDT CT: X-ray source, object manipulator, and detector. A micro-focus X-ray tube is used to provide sharp X-ray projection images even at high magnification, enabling a sharp reconstruction showing maximum detail at a given voxel resolution. At the same time, the X-ray source needs to provide sufficient intensity to enable short image acquisition times (0.5 – 1 s) and thus acceptable CT measurement times. A source size much below the voxel resolution is usually not desirable, since the corresponding high resolution X-ray image cannot be adequately captured (sampled) and the image resolution is therefore not transferred to the volumetric data. Instead it is much more important to maintain a stable source position during the CT measurement, or if thermal, mechanical or electrical drift prevents this, to accurately track the source position and compensate for the changes. Otherwise even small changes of the source position of a few dozen micrometers are sufficient to invalidate high-precision metrology results.

Another key component is a manipulator capable of positioning the object very exactly with regard to translational and rotational movement. It employs the methods of computer-aided accuracy that have been developed for coordinate measurement machines (CMMs). A rotary table with an axial run-out of below 0.1 µm ensures a highly stable and reproducible rotation.

For the flat-panel area detector, size and number of pixels are the key properties determining what size objects can be measured and what voxel resolution can be reached. For metrology, it is also very important to use a detector that shows maximum geometric fidelity, since image distortions are transferred directly to the volumetric data.

Reconstructing the object from the projection images must be done with an accuracy permitting metrology at below 1/10 of the voxel resolution, and the reconstruction process should be finished concurrent with the acquisition of the projection images. The time-consuming “backprojection step” of the reconstruction can be executed using a cluster of PCs operating in parallel, or it can be accomplished with dedicated hardware.

CALIBRATION

Large-area flat-panel X-ray detectors are produced in small volumes and suffer from some defects that are not known, or occur to a much smaller degree, in technologically similar products such as TFT monitors. E.g., it is usual to accept several complete rows or columns of defect detector pixels per detector, in addition to a large number of isolated defect pixels (up to 2% of the total number of pixels), which is unthinkable for a display device or a CCD or CMOS imager. Due to the high radiation exposure of the detector electronics during operation, new defect pixels are spontaneously created and must be accounted for.

It is therefore established practice to regularly perform automatic searches for defect detector pixels using several combinations of source-detector parameters and suitable image processing. In addition, the detector pixels exhibit individual dark currents (signal acquired in the absence of X-ray intensity) and gain factors that must also be compensated when using the images for computed tomography.

The combination of point-like X-ray source and area detector is called cone-beam geometry. For this geometry, a method of processing the X-ray images in order to reconstruct the object published by Feldkamp et al [1] has been adopted by most users. This method is very sensitive to a horizontal misalignment of source, object rotation axis and detector, therefore a regular calibration procedure is executed, usually involving a wire made from high-absorption material such as tungsten, in order to determine the horizontal alignment state.

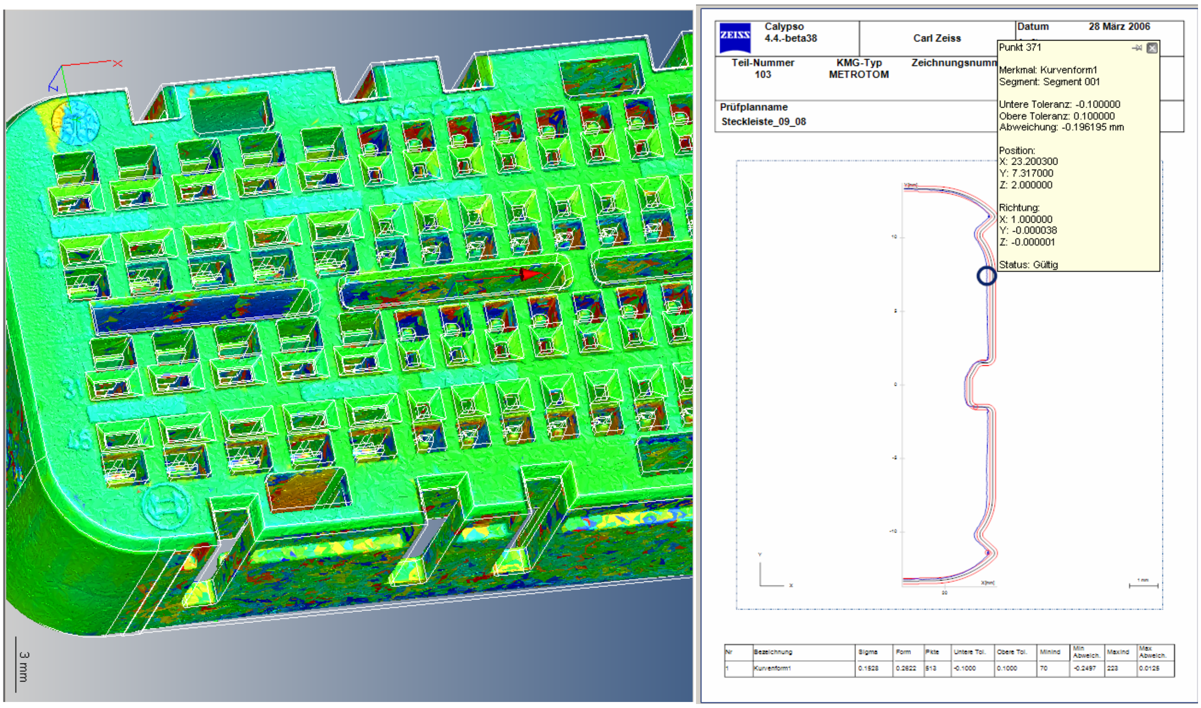
To enable a CT setup for metrology, additional calibrations are necessary. The combination of X-ray source, object and detector can be completely characterized using 9 parameters: the distance from point source to detector plane, the pixel coordinates of the normal projection of the source onto the projection, and the 6 parameters (3 rotation + 3 translation) giving the current object pose. All 9 parameters must be known with a high degree of accuracy to enable metrology substantially below the voxel resolution. For example, the voxel pitch of the volumetric data is usually chosen as a function of detector pixel pitch and magnification:

$$pitch_{voxel} = pitch_{pixel} \times \frac{d_{source-rotation\_axis}}{d_{source-\det ector}}$$

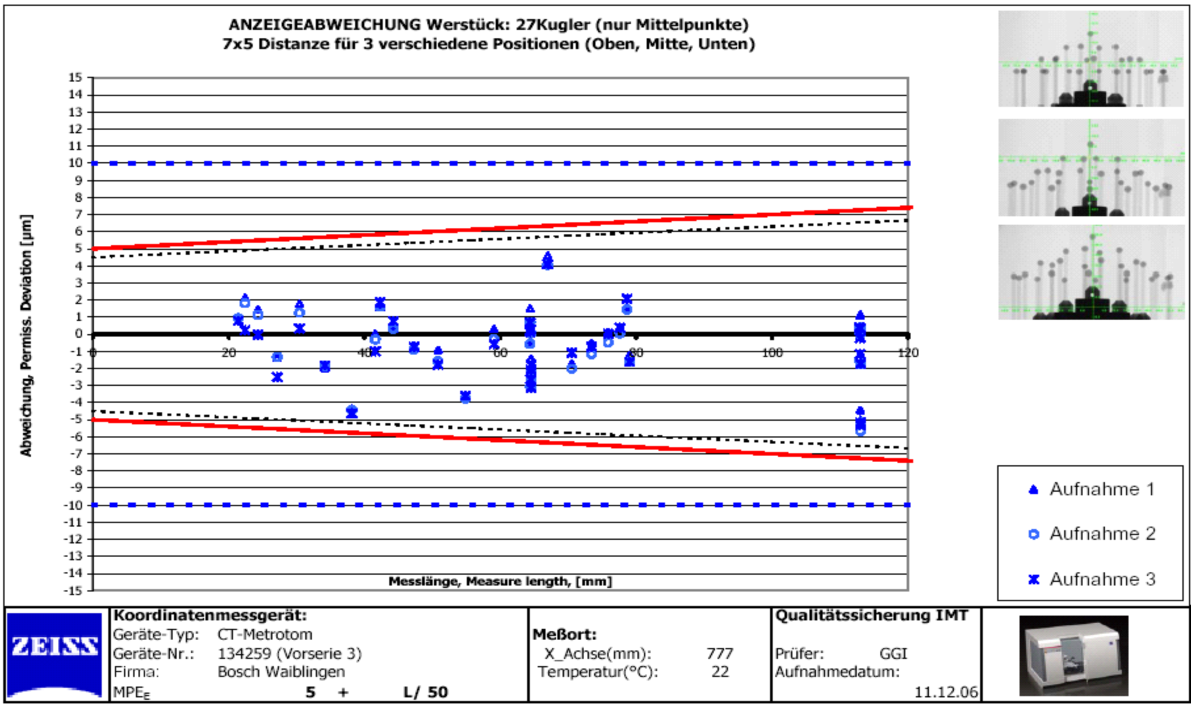
As can be seen, if the true values of the distances between source and object rotation axis resp. detector differ from the values used in the reconstruction, a wrong voxel pitch results and leads to a scaling error of the volumetric data. In the METROTOM, the two distances are known with a relative error of at most $5*10^{-5}$ to enable high-precision metrology.

METROLOGY AND VERIFICATION

Metrological evaluation of the volumetric data created by the CT is performed with the CALYPSO software. Because of the wide-band energy spectrum of the X-ray source, the volumetric data may display a locally varying level of contrast, and simple segmentation using a global gray-value threshold value is not sufficient for precision metrology. Therefore, CALYPSO employs advanced edge-finding algorithms to extract the object surface locally. Based on the CAD model of a part, the user creates an inspection plan by defining all geometric elements of interest. From this plan the software determines locations and directions of virtual probing in the CAD model, transforms them to the volumetric data, and extracts the surface points.



Once the surface points have been extracted from the volumetric data, CALYPSO offers many possibilities of visualizing the measurement results, such as color-coded model views or curve plots comparing nominal and actual surface positions.



The figure shows the CT measurement errors for a calibration object consisting of several balls, thus realizing a large number of possible measurement distances at different orientations (see inset at upper right with X-ray images). Distances between ball centers are determined from the volumetric data using the CALYPSO software and compared to values determined with a high-precision tactile-probe CMM. The difference is plotted against the nominal ball center distance and shows a deviation of a few microns between the two measurement machines, satisfying a maximum permissible error (MPE) specification for the CT of (5 + L/(50 mm)) microns, where L is the measurement length. The fact that the difference plot only shows a very small trend indicates that the X-ray source location, and thus the scale of the volumetric data, has been determined very precisely.

References:

[1] L. A. Feldkamp, L. C. Davis, J. W. Kress, Practical cone-beam algorithm, J. Opt. Soc. Am. A 1, 612 - 619 (1984).

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