Knowledge-Based System to improve dimensional CT Measurements

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Abstract
In the recent years the Computed Tomography (CT) technology thrived in the field of dimensional metrology as powerful 3D coordinate measuring technique [1]. Consequently, the CT technology is subject to the established methods and standards of metrology to assess the process variation or the uncertainty in measurement. The measurement results depend on the set values for the hardware parameters, e.g. tube voltage, tube current or exposure time, and on the work piece orientation within the measuring range [2]. These values are widely chosen based on the operators’ experience. Different operators may choose different setups leading to different measurement results. For which setup the uncertainty in measurement becomes least cannot generally be derived from the work piece documentation. Also due to the complexity of the CT, up to now there is no holistic analytical model available with which the operator can calculate the optimal parameter values.

To find adequate parameter values, a Knowledge-Based System (KBS) is proposed using a semi-empiric approach. The objective is to use available knowledge about the work piece, the CT device, the imaging process, the measurement task and previous scans. The KBS combines partly the problem solving competence of human experts with the calculation power of computers. The expert knowledge is used implicitly to structure the model and set boundaries to reduce the problem complexity. First, it is desirable that well established values for imaging parameters could be adapted to new parts. For this a search within the case database containing the parameter sets of past tomographic scan is done based on the similitude of the tomographic conditions [3]. In case of insufficient similarity to any reference case adequate parameter values are calculated based on the work piece knowledge provided by the operator and the semi-empiric process model of the tomographic scan.

Within this work the utilized model, the taken assumptions and boundary conditions are outlined together with experimental results for precision plastic parts.

Keywords: Computed Tomography, dimensional measurements, Knowledge-Based system, Set-up parameters, Prediction

1 Set-up of Industrial X-Ray Computed Tomography Measurements

Industrial X-Ray Computed tomography (CT) is increasingly used also for the measurement and quality assurance of geometric work piece features [4]. CT is a non-destructive imaging process capable to acquire the work piece holistically with very high point density. The result of the tomographic scan is a volumetric model of the work piece, approximating the 3D geometry and local density of the real part. The volumetric model can be used for versatile inspection tasks (inspection of material defects, control of assemblies and the dimensional measurement). The quality of the volumetric model is essentially influenced by the parameters of the tomographic scan, thus affecting the uncertainty of the subsequent geometric measurement. Before the tomographic scan the user has to define work piece adapted parameter values. These parameters are the tube voltage and current, the thickness of the physical filter, the number of projections, the detector gain and the exposure time [5].
Due to this large number of parameters, the finding of this adequate parameter set can be time consuming (e.g. experimental test series). The complexity of the tomographic imaging and the effects of the parameters on the projection images make it difficult for the user to assess which set-up provides the smallest uncertainty. Also expert users may be misled or can take disadvantageous decisions for a new work piece. At any rate the user influence remains high for the set-up stage. So it is preferable that the knowledge gained by undertaken scans in the past can be used to find the appropriate decision for a new part faster. The same applies to the knowledge from experimental studies to obtain the process variation $u_p$ and the bias $b$ to the calibrated value for the estimation of the uncertainty in measurement according to ISO/DIS 15530-3 [6] (Method using calibrated work pieces). In this context it is desirable to have a system that predicts adequate sets of parameters to improve the setup process. To find these parameters a knowledge based system using a semi-empiric approach is proposed in this work.

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**2 Concept of the Knowledge Based System (KBS)**

**2.1 Knowledge Based System**

The proposed Knowledge-Based System (KBS) partly emulates the ability of human experts to solve problems [7]. The KBS has the aim to propose adequate parameter values, achieve a small uncertainty in measurement and cut the experimental time to find parameter values. In a first step the KBS calculates the work piece similarity to already scanned parts stored in the case data base. The hypothesis is that similar parts require similar parameter values which in turn lead to an uncertainty in measurement in the same range. So the intention is to find similar parts in the case data base and then adapt these parameter values to the actual part. Furthermore with the KBS a more objective and reproducible approach of finding parameters is provided enabling even non-expert users to achieve quality measurement results with a CT device. The KBS was developed for single material work pieces assuming homogenous density or element distribution.

The schematic structure of the KBS is shown in Figure 1. The main components of the KBS are the knowledge base (KB) and the inference system. The communication between the KB and the user is

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Figure 1: Schematic Structure of Knowledge-Based System to predict adequate setup parameter values.
handled by a user interface. The user interface accepts input data forwarded to the inference system and returns the suggested result including an explanation offering transparency to the user.

For a new work piece the geometric and material data are loaded into the KBS. The KBS executes a similarity analysis using variables and test criterions to assess the similarity in 3 categories geometry, material and form. It compares the actual work piece data to the respective data saved in the case data base. If there is a similar work piece, the parameter values will be suggested. If there is no match, the KBS calculates parameters based on work piece data and hardware and process knowledge, which is also saved in the KB. The newly calculated parameter values are proposed to the user and finally saved to the data base. The new gained knowledge consists of the work piece data and the calculated setup parameter values. A prototype of the KBS with graphical user interface has been implemented in the development environment MATLAB 7.9.0 R2009b by Mathworks Inc., Natick (USA).

2.2 Knowledge Base

The knowledge base comprises machine specific factual knowledge (e.g. Source-Detector-Distance, Detector resolution), knowledge about the X-Ray physics of the tomographic process (e.g. tabulated attenuation coefficients, photon flux densities) and case specific knowledge. The case specific knowledge is stored in the case data base, which is a part of the KB.

**Machine specific knowledge** comprises e.g. properties and positions of x-ray source and detector that are provided in a specific file. The user chooses this file depending on the used CT system.

**Process knowledge** contains the physical and technological relations of the tomographic process. The above mentioned mass attenuation coefficients are listed in the NIST data base [8]. Information about the X-ray spectra (unattenuated and attenuated by filters) is also stored in the database. Computed tomography relies on high quality images (sharp, low noise, etc.). To achieve a sharp image the diameter of the focal spot should be smaller than half of the voxel size [9]. By this the tube voltage and the tube current which both affect the tube power and thus the focal spot size are coupled to the magnification and to the size of the work piece. The tube voltage must be high enough to generate sufficiently hard X-Rays able to fully penetrate the work piece. The focal spot must be small enough to fulfill the sampling condition. Considering these boundary conditions the maximum tube current can be calculated. Also it is important to know the parameter influence on the contrast and the Signal-Noise-Ratio (SNR) of the projection images as these are essential for high quality projection images. These are provided to the reconstruction algorithm leading to the volume module which is in turn finally used for the measurement. This influence was acquired experimentally covering the sensible parameter range of the CT device and then transferred to the KB.

The **case data base** contains case specific knowledge about already accomplished tomographic measurements. Beside the date and user name, work piece data (e.g. work piece id, company, measured features, etc.), set-up and reconstruction parameters (voltage, current, gain, reconstruction filter, etc.), control values (voxel size, SOD, etc.) and similarity data are stored.

2.3 Work Piece Representation

The work piece geometry is represented in the STL format. STL is a common CAD interface approximating the nominal geometry by triangular facets. Since the nominal geometry is only approximated, one has to choose the resolution of the STL file as demanded by the tolerances. The absorption of X-ray radiation relies on the chemical composition of the material. The composition can be characterized by three different representations (single element, proportion of elements, mass fractions of elements). For each possibility the user has to fill in a mask on the GUI or upload an ASCII-file containing the material composition and the density in g/cm³. The KBS automatically calculates the material representation. The linear absorption coefficient vs. photon energy curve is calculated by multiplying the mass absorption coefficient with the density of the work piece material. The energy dependent mass absorption coefficients are listed in a look up table.
2.4 Similarity Analysis

In order that it is permissible to adapt optimal and validated parameter values derived from an expert study to a new work piece sufficient similarity between the two work pieces is mandatory. For CT it is necessary that the similarity covers at least shape, size and material of the work piece (Figure 2) [3].

To improve the similarity analysis further also the roughness, especially for casted work pieces, should be considered. The size of the work piece affects the penetration lengths of the X-Rays within the solid material, which directly affects the remaining intensity. This influence also applies to the material composition. The shape of the work piece considers the spatial alignment of simpler regular geometries (macro geometry, cylinders, planes), which form the work piece. The effect of the shape onto the measurement is related to the size and the material distribution but also considers implicitly the effect of scattering radiation or artifacts at work piece edges. To assess the similarity of two work pieces, characteristics for the aforementioned similarity categories have to be derived and compared. For a non-ambiguous decision also a tolerance band for each characteristic is necessary.

For a similarity inquiry the stored values are read and then compared with the calculated values for the new part. Sufficient similarity between the actual part and the reference part is achieved when for all categories the values for the similarity characteristics for the actual part are within the defined tolerance band around the reference values.

To assess the similarity of shape the distance measure of Lightfield Descriptors (LFD) \( d \) of the actual part and the reference parts are compared. The test criterion is fulfilled when \( d < d_{\text{crit}} \). To calculate the LFD, parallel projections from 3 angles of view are made from the STL model returning binary images [9]. The extracted outer contour is sampled by a discrete number of points represented by complex numbers. The 2D Fourier descriptors are calculated from these points. The FD are written to a vector, which is stored in the database. The Fourier descriptors of the actual work piece are compared to the respective values of the work pieces using a Euclidean distance measure. This gives a vector of distance measures. The smallest distance values give the best match.

The similarity of scale is assessed comparing the maximum penetration length of the actual part and the reference part for the optimal alignment. The maximum penetration length is an essential indicator for the set-up of the tube voltage, which determines the hardness of the radiation. It has to be assured that the work piece is sufficiently penetrated even for the longest path length within solid material or for the path with the highest attenuation in case the local linear attenuation coefficients vary, e.g. for multi-material parts. The maximum penetration lengths are also stored in the database. The local
penetration lengths are calculated using a Matlab-based ray-tracing simulation [see also 12]. The optimum orientation is considered that specific orientation for which the maximum penetration length reaches a minimum. The control variable has to be between the penetration length $PL_{\text{min}}$ and $PL_{\text{max}}$.

To prove the similarity of the material the linear attenuation coefficients for the actual material are compared to those for the reference material for the photon energies of the emitted spectrum. For a sufficient similarity the linear attenuation coefficients have to be within a tolerance band around the reference curve. For similar penetration lengths and similar attenuation coefficients a similar attenuation can be expected. This leads to similar greyscale projection images. The suggested similarity analysis is in accordance with the major requirements of VDI/VDE 2630 Sheet 1.2. For the similarity of the measurement additionally to the similarity of the work piece also the same reconstruction and segmentation algorithm, the same registration of the point cloud and the same measurement strategy have to be applied.

2.5 Inference System

The inference system deducts adequate set-up parameter values from the knowledge of the KB and the work piece data provided by the user. The deduction is performed according to a fixed sequence and defined mathematic rules. The rules evaluate control parameters of the tomographic imaging with respect to boundary conditions and compare them to reference values. Depending on the result of the similarity analysis the setup parameter values will be chosen or calculated by the inference system. Two cases have to be distinguished. In the first case the inference system has to decide if the similarity between the actual work piece and at least one work piece from the case data base is given. Furthermore the inference system must choose the most appropriate solution of all eventual similar solutions. The similarity is assessed by the three categories mentioned in 2.4. Tolerances are required to enable the system to execute this analysis. The tolerances for the shape were experimentally obtained by classifying and surveying different views of test pieces. In this context it is relevant if a work piece is laminar, rotationally symmetric or ashlar-formed. The result of this investigation was that the distance measure $d$ of the Fourier Descriptors (FD) should be smaller than 400. If the value exceeds 400 one can assume a different category of shape. This value is valid using 320 points, as the distance measure calculation depends on the involved number of points. The similarity of size and material of the work piece can only be determined in combination since they both influence the absorption and therefore the intensity of the transmitted X-rays. Hence the tolerances are defined by the minimal intensity that reaches the detector. For the maximum penetration length (PL) of the case data base the tolerances are calculated by:

$$\Delta PL_+ < - \frac{\ln \left( -0.75 \cdot \frac{\Delta I}{I_{0, \text{permissible}}} + e^{-\mu(\lambda) \cdot \text{MaxPL}} \right)}{\mu(\lambda)} - \text{MaxPL}$$

$$\Delta PL_- < - \frac{\ln \left( \frac{\Delta I}{I_{0, \text{permissible}}} + e^{-\mu(\lambda) \cdot \text{MaxPL}} \right)}{\mu(\lambda)} + \text{MaxPL}$$

where $\Delta I/I_0$ is the maximum allowed difference in intensity between the test object and the reference object that still guarantees a sufficient similarity. The value for the utilized CT device was estimated to 0.05 based on experience and the transmission limit which still provided measurements with small variation. As a larger PL is more critical than a shorter PL, the upper tolerance contains the prefactor 0.75; $\mu(\lambda)$ is the absorption coefficient that correlates with the tube voltage from the data base.
The second case occurs when no similar part is found in the database. Then setup parameter values will be calculated and proposed by the KBS in a defined sequence. First, the x-position (Source-Object-Distance SOD) is determined whereas the magnification reaches its maximum while the whole work piece is still fully imaged on the detector for all angular positions of the rotary table. Then the object inclination angle which minimizes the maximum penetration length. A shorter PL benefits the transmission intensity and reduces beam hardening artifacts. For this calculation it is assumed that the absorption coefficient is homogenous all over the work piece. The best inclination angle and the SOD are calculated by the before mentioned ray-tracing software.

Once the work piece is optimally positioned and orientated, the X-ray spectrum has to be chosen. The tube voltage determines the maximum photon energy, which correlates directly to the maximum penetration length. The prefilter reduces the bandwidth and the intensity of the spectrum, whereas the current only scales the intensity. It is sensible to set the tube voltage in the first step. For the maximum PL of the work piece the intersection point of the material and penetration length dependant total energy flux density of a certain spectrum is determined with a given minimum total energy flux density. This device dependent minimum value was experimentally evaluated on the Zeiss Metrotom 1500 equipped with a Viscom tube to 0.00001 J/mm²/mAs which corresponds to a reduction of the factor 100 compared to the value of the unfiltered 220kV-reference spectrum (maximum energy flux density). For this value reproducible measurements and low variations were still observed. The lower operational limit is assumed at 150kV since the linear absorption coefficients increase rapidly below that energy level.

The prefilter is selected with respect to its influence on the total energy flux density and the weighted centroid distance (WDC). The WDC is the distance to the centroid of energy of the spectrum weighted by the energy flux density as a measure for the width of the spectrum. The reference is the unfiltered 150kV-spectrum, which is the narrowest spectrum in the typical operational range of the CT (150kV – 220kV). A filter shall minimize the WDC at least 10% which correlates to an over proportional 25% loss of the total energy flux density. The used filters were 0.25mm, 0.5mm, 1mm and 2mm, thick copper plates. It can be deduced that the thickness of the prefilter has to be correlated to the tube voltages. A higher voltage also increased the WDC, whereas a thicker pre filter caused the opposite effect. A look-up table contains the corresponding values. For intermittent values of the tube voltage the relative changes are interpolated. The thicker filter is selected if the WDC threshold is reached.

Regarding the sampling conditions (focal spot is half the size of a voxel) the tube power is limited. With the now fixed tube voltage the maximum current can be calculated dividing the tube power by the tube voltage. The current also has a strong linear effect on the grey values so that a bright and high contrast image can be achieved at a short exposure time.

The defined spectrum causes a grey value distribution on the detector. The parameter feedback capacitance (Detector gain) influences the relation between local intensity and assigned grey value. Decreasing the gain value increases the Root-Mean-Square (RMS) contrast but also increases the quantum noise. A small gain value means a higher amplification. The contrast grows until the detector becomes saturated. It is sensible to set a low gain factor (0.5 pF) for weak absorbing materials and a high gain factor (1.0 pF) for heavy absorbing materials. Higher gain values are possible, but do not show any significant influence anymore on the RMS contrast. The KBS calculates the optimal gain factor by comparing the characteristic curve of the linear absorption coefficient to a reference curve, gained by a measurement of the strongest absorbing plastic Perfluoroalkoxy (PFA) as a member of the weak absorbing materials group.

The exposure time defines the time a pixel collects photons. On one hand the exposure time must be high enough that the detector still works in its linear range. On the other hand the detector must not be overexposed. The overall tomography time is directly correlated to the exposure time. A longer exposure time leads to a longer tomography time. The exposure time is calculated under the boundary condition that the RMS contrast of projection images reaches at least the value 0.1. The calculation is
done by interpolating a characteristic curve that was experimentally determined using a step cylinder with known geometry and material at various parameter value combinations. The step cylinder is designed according to VDI/VDE 2630 Sheet 1.3. This investigation covered the full parameter value range. The actual work piece is then related to the cylinder with the attenuation nearest to the attenuation of the work piece giving a coarse estimation of the expected contrast.

The size of the reconstruction area influences the data volume and the reconstruction time. Therefore the reconstruction area should be only slightly larger than the work piece. To define the reconstruction area the maximum size of the work piece projection of the optimal oriented work piece considering every rotational position is calculated using the developed ray-tracing simulation software.

The number of projections also correlates to the tomographic time. A high number of projections increase the tomographic time but improve the angular sampling of the work piece. The required number of projections can be according to [10].

3 Results

A comparison of measurements based on the set-up decision of various users and measurements based on the suggestion of the KBS was made for a brush disk (component of an electrical tooth brush). The used CT device was a Metrotom 1500 (MPE: 9µm + L/50, microfocus tube, cone beam) of the Carl Zeiss IMT GmbH with the Metrotom OS operating software.

Three expert users chose the setup parameter values and work piece orientation by their own experience and knowledge about the tomographic process. The KBS supported measurement was executed by another user, who strictly followed the suggested procedure without any additional checks or corrections. The brush disk was measured 10 times by each user. For the KBS-based measurement a special holder was manufactured to keep the work piece in the suggested optimal orientation. The holder was machined from a block of hard Styrofoam. Once the work piece was adjusted it remained in that fix position for all measurements. According to the number of measurements a pre factor $m_Q(n)$ of 1.13 was assumed [11] for the uncertainty contribution $u_p$. Binning of the projection images was not allowed. The reconstruction is based on the FDK-algorithm using a Shepp-Logan-Filter. Before every measurement a bright and dark field calibration with 8 power levels was done. The ambient temperature was surveyed at $SOD_{min}$ next to the turn table during the measurement using a Conrad mantle resistance thermometer PT100 (tolerance class 1/3B according to DIN EN 60571, accuracy tolerance 0.13°C at 20°C – 30°C). The PT 100 data were acquired by a 4 channel National Instruments 24-Bit Universal Analogue Input module NI 9219, every 5 seconds. For the mathematical length correction an average temperature during the whole measurement and a linear expansion coefficient ($\alpha = 1.2 \times 10^{-4} \, 1/K$ according to ISO 11359) were assumed. The average temperature difference to the measurement temperature of 20°C was measured to 5.85 K, due to the close distance to the X-ray tube. The measurements on the tomographed data sets were performed with Calypso 4.8 of Carl Zeiss IMT GmbH. The data set was loaded in the prepared inspection plan and segmented automatically by dynamic thresholds. The work piece was calibrated using a tactile CMM Mitutoyo BLN916 (MPE: 3.3µm+L/160) with a sphere diameter of 1mm, increment 0.015-0.020 mm and a probing force of 0.1N.
Figure 3 shows the tooth brush disk. Table 1 shows calibration values and exemplary measurement results of two selected features (B1, Z1). Z1 is the diameter of the brush disc. B1 is the diameter of the cylinder located in the middle of the brush mount. The measurement uncertainty was estimated by the method of calibrated work pieces and is listed in table 2 [6].

### Table 8: Results of selected features of the tooth brush disk

<table>
<thead>
<tr>
<th>Feature</th>
<th>Cal. Value</th>
<th>User A</th>
<th>User B</th>
<th>User C</th>
<th>KBS</th>
</tr>
</thead>
<tbody>
<tr>
<td>x_cal [mm]</td>
<td>b [mm]</td>
<td>σ [mm]</td>
<td>b [mm]</td>
<td>σ [mm]</td>
<td>b [mm]</td>
</tr>
<tr>
<td>B1</td>
<td>1.4811</td>
<td>-0.0208</td>
<td>0.0023</td>
<td>0.0014</td>
<td>0.0009</td>
</tr>
<tr>
<td>Z1</td>
<td>13.3716</td>
<td>0.0209</td>
<td>0.0037</td>
<td>0.0002</td>
<td>0.0006</td>
</tr>
</tbody>
</table>

### Table 9: Measurement Uncertainty of selected features of the tooth brush disk

<table>
<thead>
<tr>
<th>Feature</th>
<th>Uncertainty contribution</th>
<th>User A</th>
<th>User B</th>
<th>User C</th>
<th>User D</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>u_cal</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td></td>
<td>u_p</td>
<td>0.0026</td>
<td>0.0003</td>
<td>0.0121</td>
<td>0.0033</td>
</tr>
<tr>
<td></td>
<td>u_w</td>
<td>0.0018</td>
<td>0.0018</td>
<td>0.0018</td>
<td>0.0018</td>
</tr>
<tr>
<td></td>
<td>u_b</td>
<td>0.00007</td>
<td>0.00007</td>
<td>0.00007</td>
<td>0.00007</td>
</tr>
<tr>
<td></td>
<td>U</td>
<td>0.00664</td>
<td>0.00416</td>
<td>0.02455</td>
<td>0.00778</td>
</tr>
<tr>
<td>Z1</td>
<td>u_cal</td>
<td>0.0005</td>
<td>0.0005</td>
<td>0.0005</td>
<td>0.0005</td>
</tr>
<tr>
<td></td>
<td>u_p</td>
<td>0.0043</td>
<td>0.0008</td>
<td>0.0027</td>
<td>0.0010</td>
</tr>
<tr>
<td></td>
<td>u_w</td>
<td>0.0033</td>
<td>0.0033</td>
<td>0.0033</td>
<td>0.0033</td>
</tr>
<tr>
<td></td>
<td>u_b</td>
<td>0.0006</td>
<td>0.0006</td>
<td>0.0006</td>
<td>0.0006</td>
</tr>
<tr>
<td></td>
<td>U</td>
<td>0.01095</td>
<td>0.00697</td>
<td>0.00867</td>
<td>0.00707</td>
</tr>
</tbody>
</table>

The measurement results of User A show significant systematic deviations. This can be explained since User A is less experienced than User B. The smallest process variation can be found in the results of User B although the systematic deviation of diameter Z1 is relatively large.

The KBS decreased the systematic variation compared to User A whereas for B1 the process variation was slightly higher. Comparing the measurement uncertainty on condition that b is compensated, the KBS is on third place for the diameter B1 and for the diameter Z1 on second place, close to the result of User B. The improvement by the KBS was observed on average throughout the measurements of other work pieces (e.g. POM step cylinder) and features that are not shown in this paper. For instance User B could not accomplish the best results for all features of the step cylinder.
4 Conclusions

The comparison of the measurements based on the set-up decision of human users and based on the suggestion of the KBS demonstrated the capability of the KBS to propose adequate setup parameter values for typical complex plastic parts. Supported are the relevant parameters for the imaging process and the work piece alignment. Especially compared to less experienced users the KBS reduced the systematic deviations significantly. The KBS is a useful tool for the inspection planning to reduce setup time and therefore increase the efficiency of the CT device. Also it can provide a more objective and transparent parameter set-up. Currently the KBS is limited to homogeneous materials and CT devices with cone beam. Strictly speaking the applied semi-empiric black box approach is not a mathematical optimization of the uncertainty in measurement. However, it can reduce process effects on the variance and the bias of the measurement process by suggesting an appropriate part-adapted parameter set-up as has been proven experimentally.

Acknowledgements

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