Publishable Summary for 17IND08 AdvanCT
Advanced Computed Tomography for dimensional and surface measurements in industry

Overview

Computed tomography (CT) is a contact-free measurement method which allows the complete geometry of objects to be determined. This includes the inner and outer geometry and the surface texture, all of which are typically not fully accessible by other measurement methods. There are a broad range of applications for CT, which include macro- and microfabrication, the automotive and telecom industries, and additive manufacturing.

In order to support future dimensional metrology in advanced manufacturing, this project developed traceable CT measurement techniques for dimensions and surface texture. In addition, current issues regarding traceability, measurement uncertainty, sufficient precision/accuracy, scanning time, multi-material, surface form and roughness, suitable reference standards, and simulation techniques were addressed by this project.

Within the framework of the project, significant progress was made in increasing the accuracy and traceability of CT measurements. New fields of application were opened up through the CT measurement of roughness and the reduction of scanning time.

Need

Over the past few years, CT has increasingly been used for dimensional measurements of both the inner and outer geometry of workpieces, such as cavities and parts in mounted assemblies. Such workpieces originate from macro- and microfabrication, the automotive and telecommunication industries, and additive manufacturing, thereby showing the potential broad use of CT.

Despite the rapidly increasing use of CT in industry, the measurement errors of most CT systems are too large and needed to be substantially reduced, i.e. by a factor of 2 – 8, to 10 µm even when measuring mid-size parts (approx. 1000 cm^3). However, the traceability of CT results needed to be established and methods to estimate the measurement uncertainty needed to be developed. Further to this, the time required to perform CT measurements and data evaluation needed to be reduced from hours to minutes if CT is to be more widely used in industry.

Guidelines and standards, such as standardised test procedures and specifications, are also needed to support a fair and competitive market and users of industrial CT. The German standardisation committee VDI/GMA 3.33 has developed some national guidelines (VDI/VDE 2630-series) for dimensional measurements using industrial CT. In addition, an international standard defining acceptance and reverification tests for CMS using the CT principle is currently under development by ISO TC213 Dimensional and geometrical product specifications and verification WG10 Coordinate measuring machines, which will become part of the ISO 10360-series. Therefore, this project supported these standardisation bodies by providing input to them on inline CT and multi-material measurements.

The above needs are underpinned by the EURAMET roadmap and Strategic Research Agenda and a report published by Frost and Sullivan in 2015 on “Strategic Analysis of Computed Tomography Technology in the Dimensional Metrology Market” In this report, the key areas identified for developing a broader use of industrial CT in industry are “Capabilities to improve measurement resolution”, “Support for multi-material complexity” and “Reduced measurement time (scanning and reconstruction)”.

Objectives

The overall goal of this project was to develop metrological capacity in Advanced Computed Tomography for dimensional and surface measurements in industry. The specific objectives of this project were:

1. To develop traceable and validated methods for absolute CT characterisation including the correction of geometry errors by 9 degrees of freedom (DoF). This included the development of reference standards, traceable calibration methods and thermal models for instrument geometry correction, as well as the correction of errors originating in the X-ray tube and the detector in order to improve CT accuracy.
2. To develop improved and traceable methods for dimensional CT measurements with a focus on measurements of sculptured / freeform surfaces, roughness, and multi-material effects including supplementary material characterisation.
3. To develop fast CT methods for inline applications based on improved evaluation of noisy, sparse, few, or limited angle X-ray projections, and reconstruction methods. This was undertaken using a reduced number of projections from well-known directions and include enhanced post-processing.
4. To develop traceable methods for uncertainty estimation using virtual CT models and Monte-Carlo simulations. Batch simulation and evaluation capacities was improved. The determination of accurate model parameters was necessary for a reliable uncertainty estimation and this was performed for different CTs and it was systematised. Corrections for several artefacts were developed. Uncertainty was estimated by Monte-Carlo based simulation and verified using the calibrated standards developed in WP1.
5. To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (accredited laboratories, instrumentation manufacturers), standards developing organisations (e.g. ISO TC213 WG10, VDI-GMA 3.33 Technical Committee Computed Tomography in Dimensional Measurements) and end users (e.g. plastic manufacturers, automotive, telecommunication, medical and pharmaceutical industries and metrology service providers).

Progress beyond the state of the art

CT has great potential for the quantitative evaluation of industrial components, compared with conventional measurement technologies, due to its capability to measure both external and internal features simultaneously and non-destructively. Over the last few years, CT has been increasingly used for dimensional measurements of both the inner and outer geometry of industry workpieces. However, both the quality and speed of the measurements are not sufficient for end users and currently hampers the uptake for industries with stringent tolerance requirements (<0.01 mm). In order to increase the measurement speed, manufacturers of CT systems are working on accelerated measurement procedures and improved reconstruction algorithms. However, these are currently only suitable for CT measurements with low accuracy requirements.

This project developed CT as a next generation dimensional and surface metrology tool for industrial applications. Work was undertaken to significantly improve both the quality and efficiency of measurements performed using CT in order to meet industrial requirements for an improvement of the accuracy by a factor of 2 - 10 and a reduction of the measurement time to a few minutes or less.

This project established a unique 9-degrees-of-freedom *in situ* metrology CT system, investigated geometrical errors as well as thermal stability, X-ray tube and detector-based effects and developed new corresponding corrections. The project also investigated state-of-the-art correction methods for CT image-forming artefacts, (e.g. cone beam artefacts, metal artefacts, beam hardening artefacts or scattering artefacts) and investigated the robustness, efficiency, and possible standardisation of these correction methods for dimensional metrology. Further to this, well parameterised virtual CT models and Monte-Carlo simulations were developed by the project in order to be able to predict measurement errors and to determine the measurement uncertainty of measurements performed using CT.

This project pioneered the use of CT for surface measurements; including both surface form and the evaluation of surface texture parameters based on ISO 25178 (Geometrical product specifications (GPS) — Surface texture). The influence of reconstruction methods, data interpolation and filtering was also studied by the project and a range of surface parameters was tested for the characterisation of the surface texture of advanced manufactured components e.g. additively manufactured hydraulic components.

Conventional CT scans that take about an hour to perform cannot meet the industrial requirements for fast inline measurements. An example of one such bottleneck of conventional CT is the filtered back projection reconstruction algorithm, which requires thousands of projection images to be assessed and hence is not suitable for industrial production lines. Furthermore, the filtered back projection reconstruction algorithm also suffers from measurement artefacts due to e.g. beam hardening and X-ray scattering. Therefore, this project worked to improve the speed of CT measurements, to the order of minutes or less. The project's aim was to improve the speed whilst also maintaining the quality of the reconstruction by applying advanced sensing reconstruction algorithms to cope with sparse, noisy measurement data from a reduced number of projections or limited projection angles. Modern machine learning techniques and theories were used to optimise the parameters used for reconstruction.

Results

To develop traceable and validated methods for absolute CT characterisation including the correction of geometry errors by 9 DoF. This included the development of reference standards, traceable calibration methods and thermal models for instrument geometry correction, as well as the correction of errors originating in the X-ray tube and the detector in order to improve CT accuracy.

Throughout the project, more than ten reference standards, optimised for different tasks, have been developed and characterised. These were 2D-standards of different size for easy determination of the magnification, multi-sphere standards for a complete characterisation of the CT geometry, reference standards made of different materials (metal, glass, etc) to determine the performance of CT systems, and standards for XCT surface texture calibrations. Corresponding software tools for the reference standards have also been developed which can be used to characterise CT geometries.

In the validation of the easy determination of the magnification using 2D-standards, very small relative deviations in the order of 1 10^{-5} could be achieved compared to the conventional method.

In order to study the influence of temperature variations on CT geometry, temperature measurement systems were installed on three CT systems. The measurements obtained from these CT systems and extensive thermal modelling were finally used to develop effective mitigation strategies for temperature effects on CT geometry. The influence of complex error sources, such as the X-ray tube and the detector, on CT measurements were investigated and used for corrections and improved measurement uncertainty estimations. In particular, strategies to mitigate the effect of X-ray tube drift have led to important improvements for high-magnification CT scans.

All these results represent a significant contribution towards the goal of improving the accuracy of dimensional CT by a factor of 2 – 8. Using a dedicated CT metrology system, the standard deviation of unidirectional CT measurements from tactile reference values was reduced by a factor of two (from 0.2 µm to 0.1 µm, magnification: 96x). Optimised water-cooling reduced mechanical drifts in the CT machine geometry by a factor of 4 (from 8 µm to 2 µm). The effect of this improvement on geometrical measurements depends on the respective magnification. The accuracy of the geometric magnification determined with the novel 2D standards reached 2×10^{5}. The project's reference standards are now used to establish traceability for CT measurements. Furthermore, they have enabled two partner NMIs (VTT and METAS) to provide new CT-based calibration services, which started during the life of the project. PTB will be able to offer these new calibration services by early 2023.

All tasks in Objective 1 were achieved.

To develop improved and traceable methods for dimensional CT measurements with a focus on measurements of sculptured / freeform surfaces, roughness, and multi-material effects including supplementary material characterisation.

To investigate the CT measurement of freeforms a pair of freeform artefacts made from titanium or plastics was scanned with different CT systems and evaluated against a tactile reference measurement. Different registration methods (i.e., 3-2-1 feature-based or best-fit of surfaces) produced very different results from the same data. This is problematic for freeforms, where feature-based registration may not be an option. The issue was overcome by applying an image correction from objective 4, yielding consistent results regardless of the registration method.

A freeform may not be describable by mathematical models. Model-based and point-based evaluation strategies were tested. While the strategy had some impact, the key to obtaining results comparable to a tactile reference was an accurate scale correction. Magnification was determined using a substitute part (from objective 1) or using reference spheres on the freeform parts themselves. Both approaches worked well and greatly improved the outcome. The scale correction also establishes the link to the traceability chain.

For roughness characterisation, an additively manufactured (AM) standard was created. This standard has four faces with spheres, one-sided steps and surface texture features. The surfaces have different *Ra* parameters (10 µm to 40 µm). For traceability purposes, 2D profiles were measured by contact stylus as a reference and CT. Different *λs* and *λc* filters were investigated for the evaluation of the CT results. The uncertainty was evaluated according to GUM.

A further study looked at areal data using three different CT systems to investigate the behaviour of different systems with respect to roughness measurement with CT. This yielded repeatable results with small uncertainties. Areal methods provide superior statistical relevance to profile methods. Areal methods also overcome the issue that it is difficult to manufacture AM reference standards with uniform surface textures. The methods developed here were used in case studies on different parts, e.g., polymer parts (LEGO) or internal surfaces of small bore needles.

Multimaterial objects with very different (e.g. plastic / steel) or with small to moderately different (e.g. ceramics / aluminium) absorption coefficients were investigated with the goal of demonstrating traceable CT measurements of multimaterial objects that are typically composed of two materials. The versatility and limits of common, single-threshold surface determination algorithms were investigated in order to establish boundaries for their effective application to multimaterial objects.

Following an extensive literature review, promising metal artefact correction methods were compared with respect to measurement errors. The comparison showed that metal artefact correction can also improve any corrupted data that is used for dimensional measurements. However, measurement errors remain significant and the effectiveness of the corrections depends on the quality of the original data.

Additional material characterisation was undertaken by synchrotron-CT using monochromatic X-rays to evaluate the effect of multi-material and different X-ray spectra on measurement uncertainty. The analysis of the experimental data revealed the significant impact different X-ray spectra can have on the uncertainty for multi-material objects. This will provide traceability for dimensional measurements with synchrotron-CT.

X-ray phase contrast, which is prevalent in high resolution CT scans was investigated. Experiments were conducted to produce varying degrees of the effect and apply corrective algorithms in order to evaluate their effects on the results and measurement uncertainty.

All tasks in Objective 2 were achieved except the competition of the investigations on the influence of X-ray refraction and phase retrieval algorithms on dimensional measurements with synchrotron X-ray computed tomography.

To develop fast CT methods for inline applications based on improved evaluation of noisy, sparse, few, or limited angle X-ray projections, reconstruction methods. This was undertaken using a reduced number of projections from well-known directions and include enhanced post-processing.

To shorten X-ray-CT (XCT) scan times to minutes or less, the number of projection images acquired, and the image exposure time must be reduced significantly. This requires advanced reconstruction algorithms to handle data with a limited number and noisy projection images. The project has reviewed the state-of-the-art algorithms to reconstruct noisy, sparse, few or limited angle X-ray projections. Three advanced reconstruction algorithms have been successfully developed; one is the fast version of the TV constrained reconstruction algorithm FISTA, one is a deep learning algorithm using convolution neural network (CNN) and one is based on freely available platform TensorFlow (used a U-net).

A user-friendly open-source reconstruction software, Tomographic Iterative GPU-based Reconstruction Toolbox (TIGRE), has been enhanced by the project. TIGRE is an open-source toolbox for fast and accurate 3D tomographic reconstruction for any geometry. Its focus is on iterative algorithms for improved image quality that have all been optimised to run on GPUs for improved speed. The speed of reconstruction for TIGRE was significantly improved during the project by implementing multiple-GPUs into the software. Any installation and compatibility issues have been investigated and resolved by the project so as to allow users to easily access the enhanced TIGRE software which is now available in both MATLAB and Python.

In order to test the algorithms for dimensional metrology purposes, a range of reference samples have been reviewed and down selected to have a good coverage of different geometries. Based on the selection, test samples have been prepared and circulated within the consortium for simulations and CT scans. Both simulation and experimental data are available for testing different acquisition modalities (e.g. sparse projections) and reconstruction algorithms in order to investigate and improve current methods of performing fast CT. The work successfully demonstrates the feasibility of fast CT for a reasonable quality in quantitative evaluation.

To develop traceable methods for uncertainty estimation using virtual CT models and Monte-Carlo simulations. Batch simulation and evaluation capacities was improved. The determination of accurate model parameters was necessary for a reliable uncertainty estimation and this was performed for different CTs and it was systematised. Corrections for several artefacts were developed. Uncertainty was estimated by Monte-Carlo based simulation and verified using the calibrated standards developed in WP1.

To facilitate simulation-based uncertainty estimations the simulation software aRTist has been extended by an add-on module to easily design large simulation jobs of Monte-Carlo experiments with deterministic and statistical parameter variations. This enables more realistic simulations by modelling geometrical deviations from the standard trajectory of real computed tomography (XCT) systems and generally supports virtual XCT with arbitrary trajectories. An interface to external evaluation software has been defined and tested between aRTist and two commercial CT reconstruction programs, which provides each projection with an individual projection matrix. Additionally, the detector model has been improved. With respect to the computational effort of virtual CT batch simulations, this can be planned and distributed among several computers. This includes the use of Supercomputers, which has been tested at the high-performance computing cluster IRIDIS5.

A simulation-based approach of estimating the uncertainty of an XCT measurement requires a representative model of the XCT system including deviations from the ideal geometry. The virtual model needs to be integrated into the dimensional XCT processing chain. Two experimental methods have been evaluated to integrate geometrical deviations into an aRTist simulation. A full iterative automation has been achieved to generate a representative model of an XCT system. The cumulated surface distance (CSD) of the resulting surface deviations histograms compared to a CMM corrected STL model has been identified as a suitable parameter to qualitatively describe the similarity between simulated and measured data.

A systematic overview of relevant origins of image forming artefacts, identifying more than ten distinct types, has been compiled. Two dominant static image artefacts have been treated by deconvolution: a corona artefact due to scattering apertures acting as a parasitic source, and visible light transport in the detector's scintillator (blooming, halo, scatter). A suppression of the effects in case of the light transport by a factor of 10, and in case of the gain-drift by a factor of five, has been realised by deconvolution. Besides the numerical correction, a suppression of the corona effect by a factor of 10 was possible by a constructive enhancement of the source's aperture.

Artefacts originating from scatter radiation were examined by a generic virtual CT software model based on the GEANT4 Monte Carlo simulation toolkit. Scattering has been investigated with origin in the sample object, the entrance window of the detector, the detector material (scintillator) itself and the silicon attached at the backside. Additional full-scale Monte-Carlo simulations have been used to determine the required number of photons for the approximate scatter simulation.

Furthermore, the applicability of virtual XCT for uncertainty estimation has been evaluated for XCT scans with arbitrary trajectories by robotic manipulators, and for surface roughness measurements.

The objective was achieved, except for the verification of the simulation-based uncertainty against empirical measurements.

Impact

Project results have been presented in 36 presentations and posters at national and international conferences and an additional seven are planned in 2022 including specialised CT events such as Dimensional X-ray Computed Tomography (dXCT) 2018, 2019, 2020, 2021 and the Conference on Industrial Computed Tomography (ICT) 2019, 2020 and 2022. Other invited presentations have also been given at the Micro and Nanotomography Symposium: 3D Imaging for Industry in Switzerland and the Seminar Series in XCT in the UK.

Fourteen open access publications and proceedings have been published and an additional eight have been submitted by the consortium. Further to this the project's website was regularly updated and is available at www.ptb.de/empir2018/advanct

Impact on industrial and other user communities

The results of this project can be used by a broad range of end users in industry such as manufacturing (in particular manufacturers of plastic parts fabricated by injection moulding), microfabrication (e.g. watch parts), automotive (e.g. cast parts, electronic components, fuel injection components), telecommunication (e.g. fibre-optic and high frequency connectors), medical (e.g. ophthalmology, dental implants), pharmaceutical (e.g. lab on a chip), and metrology service providers.

The project's significant improvements in the measurement accuracy and timeframe of CT measurements (objectives 1, 3 & 4) will be of particular interest to industrial end users, who are in urgent need of inline CT measurements and better quality control. Similarly, the potential use of CT to evaluate surface roughness (objective 2) promises to greatly benefit manufacturing.

The project has engaged directly with industry through its stakeholder committee which included members from Nikon Metrology Europe NV, Messtronik GmbH and The Manufacturing Technology Center. The consortium also included industrial partners Bosch, LEGO, NovoNordisk, Volume Graphics (VG), Werth Messtechnik, Yxlon International and Carl Zeiss, who participated in case studies to demonstrate the direct applicability and benefits of the project's improved CT measurements. The case studies include (i) NovoNordisk – The relationship between surface roughness and flow rate in small bore needles, (ii) LEGO – 3D surface texture parameterisation of small internal bores for mould tool conformal cooling and (iii) Bosch - traceable CT measurement of automotive parts.

To help disseminate the project's results to industrial end users the project collaborated with the dXCT society and hosted a workshop on “Advanced XCT for dimensional metrology- reconstruction algorithms” in December 2020. The workshop disseminated the latest developments in the reconstruction of XCT to more than 80 participants from 38 different organisations (11 universities and 27 commercial companies or research institutes worldwide).

Further to this the project has produced articles for end users on CT in METinfo and IEEE Transactions, as well as a promotional video on Computed tomography “Small parts reveal their shape” (https://youtu.be/e3pGsZK1jLI)

Impact on the metrological and scientific communities

The main impact of this project for the metrological and scientific communities will be the provision of traceability for CT measurements and an increase in their accuracy. To support this the project has hosted a workshop at The European Society for Precision Engineering and Nanotechnology (euspen) on Uncertainty in dimensional XCT. The euspen workshop attracted approximately 50 participants from industry and science.

The results will also enable NMIs to introduce new CT calibration services at partners PTB, VTT and METAS. Indeed, VTT has already started to provide XCT measurement services for industrial components and METAS has launched dimensional XCT feasibility studies and first services for end users.

The reference standards developed in objective 1 are being used for calibration of measurements (at VTT). Thus, the accuracy of measurements, where pre-existing standards were unsuitable, could be increased.

Further to this, the project has created impact through the uptake of the accuracy improvements by users from outside of the consortium who aim to improve their hardware and software. To support this the project has provided training to the scientific community on high-end industrial CT Software ‘VG STUDIO MAX and VG in LINE - improved and efficient use’ and ‘Using simulator aRTist’ (objective 4). The improved TIGRE software (objective 3) is freely available and open source.(https://github.com/CERN/TIGRE)

Impact on relevant standards

This project enabled better comparison of CT systems by providing input to improved standardised testing procedures. Unlike current standardised test procedures which only include geometrical measurements of existing or developmental monomaterial objects, this project provided input on test procedures that take multimaterial objects and surface roughness evaluation into account.

The project provided input to and helped to accelerate the establishment of ISO standards within the field of CT for geometrical measurements of monomaterial and multimaterial objects. Indeed, the project liaised with ISO TC213 WG10 "Coordinate measuring machines", ISO TC 261 "Additive manufacturing".

In addition, the project has provided input to standardisation bodies such as ISO TC213 WG10 (Coordinate metrology) BIPM CCL (Length), VDI/GMA FA 3.33, DIN NA 152-03-02-12 UA KMT (Coordinate metrology), ASTM E07 (Nondestructive Testing) and METSTA GPS (a national GPS group).

Longer-term economic, social and environmental impacts

The long-term impact of this project will be through the support of European manufacturers (e.g. in the automotive and healthcare industry), who require advanced measurement capabilities for quality control and development. In addition, the project's advanced CT measurement capabilities, (e.g. the measurement of complete workpiece geometry, without damage, within a shorter timeframe) should also support the development of new production technologies for electro- and mechanical components.

The project's support for the increased use of industrial CT systems will help to strengthen the market position of European CT manufacturers. Currently, four of the top five manufacturers in the world market for CT dimensional metrology are European.

Better CT measurements should lead to higher quality, longer-lasting products and the improvement of the safety of household appliances parts for the automotive industry and medical products. The case studies investigated in this project illustrate the broad range of applications of CT. They include healthcare products for insulin injection (a life-saving application) and LEGO toys that have inspired creativity in children (and adults) for generations.

By increasing end users' confidence on CT measurements, this project will help to increase the use of CT in industry and hence improve product development and processes. The use of traceable XCT measurements in quality assurance and quality control should also lead to earlier detection of defective parts. Hence chances to reuse materials and components would increase, thereby improving efficiency and reducing waste. For example, the emissions of combustion engines are dependent on the dimensional characteristics of fuel injection systems. Therefore, better measurements of fuel injection system components should lead to reduced emissions.

List of publications

[1]. Bircher, B.A. et al., *CT geometry determination using individual radiographs of calibrated multi-sphere standards*, Proceedings iCT - 9th Conference on Industrial Computed Tomography, 2019 https://www.ndt.net/article/ctc2019/papers/iCT2019_Full_paper_43.pdf

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[10]. Lohvithee, M. et al., *Ant Colony Based HyperParameter Optimisation in Total Variation Reconstruction in XCT*, Sensors, https://doi.org/10.3390/s19245461

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[12]. Bircher, B. et al., *Measurement of temperature induced X-ray tube transmission target displacements for dimensional computed tomography*, Precision Engineering, https://doi.org/10.1016/j.precisioneng.2021.06.002

[13]. Chrétien, S. et al., *Fast hyperparameter calibration of sparsity enforcing penalties in Total Generalised Variation penalised reconstruction methods for XCT using a planted virtual reference image*, Mathematics, https://doi.org/10.3390/math9222960

[14]. Sun, W. et al., *Establishment of X-ray computed tomography traceability for additively manufactured surface texture evaluation*, Additive Manufacturing, https://doi.org/10.1016/j.addma.2021.102558

[15]. Obaton, A.-F, et al., *Comparison campaign of XCT systems using machined standards representative of additively manufactured parts*, Proceedings of the 11th Conference on Industrial Computed Tomography (iCT) 2022, https://www.ndt.net/article/ctc2022/papers/ICT2022_paper_id207.pdf

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This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/

Project start date and duration:		01 June 2018, 42 months
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Internal Funded Partners: 1 PTB, Germany 2 BAM, Germany 3 DTI, Denmark 4 FSB, Croatia 5 LNE, France 6 METAS, Switzerland 7 NPL, United Kingdom 8 VTT, Finland	External Funded Partners: 9 CEA, France 10 Empa, Switzerland 11 FAU, Germany 12 UBATH, United Kingdom 13 UNOTT, United Kingdom 14 UoS, United Kingdom	Unfunded Partners: 15 Bosch, Germany 16 LEGO, Denmark 17 NovoNordisk, Denmark 18 VG, Germany 19 Werth, Germany 20 Yxlon, Germany 21 Zeiss, Germany
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