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 will develop 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 will be addressed by this project.

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 need 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 is yet to be established and methods to estimate the measurement uncertainty need to be developed. Further to this, the time required to perform CT measurements and data evaluation needs 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 will support 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 is to develop metrological capacity in Advanced Computed Tomography for dimensional and surface measurements in industry. The specific objectives of this project are:

1. To develop traceable and validated methods for absolute CT characterisation including the correction of geometry errors by 9 degrees of freedom (DoF). This will include 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 will be 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 will be improved. The determination of accurate model parameters is necessary for a reliable uncertainty estimation and this will therefore be performed for different CTs and it will be systematised. Corrections for several artefacts will be developed. Uncertainty will be 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 industrial uptake of the technology.

This project is developing CT as a next generation dimensional and surface metrology tool for industrial applications. Work is on-going in the project to significantly improve both the quality and efficiency of measurements performed using CT in order to meet industrial requirements of an improvement of the accuracy by a factor of 2 - 8 and a reduction of the measurement time to a few minutes or less.

This project is in the process of establishing a full 9 degrees of freedom in situ metrology CT system, investigating geometrical errors as well as thermal stability, X-ray tube and detector-based effects and their corresponding corrections. The project is also investigating 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 is investigating the robustness, efficiency, and possible standardisation of these correction methods. Further to this, well parameterised virtual CT models and Monte-Carlo simulations are being 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 is pioneering 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 is also being studied by the project and a range of surface parameters are being tested for the characterisation of the surface texture of advanced manufactured components e.g. additively manufactured hydraulic components.

Conventional CT scans that take hours 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 is working to improve the speed of CT measurements, to the order of minutes or less. The project's aim is to do 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 are being 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 will include 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.

So far more than ten reference standards optimised for different tasks have been developed and characterised. These include 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 a standard for XCT surface texture measurement calibration. Corresponding software tools for the reference standards have also been developed and are ready to be used to characterise CT geometries.

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 are now being 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 was also investigated and are being used to develop corrections and improved measurement uncertainty estimates for CT measurements. In particular, strategies to mitigate the effect of X-ray tube drift has already led to important improvements for high-magnification CT scans.

All of 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 2 (from 0.2 µm to 0.1 µm, magnification: 96x). Optimised water-cooling reduced mechanical drifts in the CT machine geometry were reduced 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 can be used to establish traceability for CT measurements. Furthermore, they will enable three partner NMIs (PTB, VTT and METAS) to provide new CT-based calibration services.

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.

The project has selected two freeform artefacts made of Titanium and plastics suitable for dimensional CT measurements and associated measurement tasks at the embodied hyperbolic paraboloids. Using the selected freeform artefacts and measurement methods, data is currently being collected for comparative dimensional CT measurements in order to investigate the performance of CT systems measuring freeforms.

For surfaces, the project is establishing a numerical approach to extract and analyse surface texture data from CT, which will be in compliance with the standard approach of surface roughness analyses. The limitations of roughness measurements undertaken using CT are being investigated and strategies to compare measurement results to traceable instruments are currently being studied.

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 corrupted data used for dimensional measurements. However, measurement errors remain significant and the effectiveness of the corrections depends on the quality of 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.

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 will be 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 state-of-the-art algorithms to reconstruct noisy, sparse, few or limited angle X-ray projections. Based on the results of the review, three advanced reconstruction algorithms have been successfully developed; one based on total variation, one on machine learning and one on multiple graphics processing unit (GPU) based approaches.

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.

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

The project's traceable methods for uncertainty estimation using virtual CT models and Monte Carlo simulations will be incorporated into the simulation software Analytical RT Inspection Simulation Tool (aRTist), which is commercially available from BAM (http://www.artist.bam.de/). These improvements include tools to enable simulations to be matched with the characteristics of real CT devices, including non-standard trajectories. The uncertainty of CT measurements will be estimated based on the simulation and tools have been developed for planning and running large Monte-Carlo simulation batches on distributed systems, and for use with external data evaluation software.

The additional software tools incorporated in aRTist are now available for testing. They should allow the user to design large simulation jobs of Monte-Carlo experiments with deterministic and statistical parameter variations. To test this, an interface for external evaluation software has been defined and tested between aRTist and two commercial and one free CT reconstruction programs. In addition to the software tool development in aRTist, the project has also investigated approaches to systematise the process of model adaptation to real CTs.

Further to this, a generic virtual CT model has been used to assess the influence of specific system and measurement parameters. X-ray simulation tools have been installed on a high-performance computing cluster to enable a full-scale Monte-Carlo simulation study to be carried out. Three reference objects have been produced, calibrated, and modelled to support the model parameter determination. Two of the reference objects have a size below 30 mm while the third is larger. Algorithm-based correction methods for uncertainty improvements are currently in development and a correction filter for blooming artefacts has been produced.

Impact

So far, the project's results have been presented in 25 presentations and posters at conferences including specialised CT events such as Dimensional X-ray Computed Tomography (dXCT) 2018, 2019, 2020 and the Conference on Industrial Computed Tomography (ICT) 2019 and 2020. 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.

Twelve open access publications have been produced by the consortium. Further to this the project's website is 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 is engaging directly with industry through its stakeholder committee which includes members from Nikon Metrology Europe NV, Messtronik GmbH and The Manufacturing Technology Center. The consortium also includes industrial partners Bosch, LEGO, NovoNordisk, Volume Graphics (VG), Werth Messtechnik, Yxlon International and Carl Zeiss, who are participating 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 (objective 1). 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 will create impact through the uptake of the accuracy improvements by users from outside of the consortium who intend to improve their hardware and software. To support this the project has already 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 currently being circulated among the project partners. Afterwards it will be made freely available and open source.

Impact on relevant standards

This project will enable 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 will also provide input on test procedures that take multimaterial objects and surface roughness evaluation into account.

The project will provide input to and should help to accelerate the establishment of ISO standards within the field of CT for geometrical measurements of monomaterial and multimaterial objects. Indeed, the project is already liaising with ISO TC213 WG10 "Coordinate measuring machines", ISO TC 261 "Additive manufacturing".

In addition, the project has provided input to standardisation bodies such as BIPM CCL (Length), VDI/GMA FA3.33, DIN NA 152-03-02-12 UA, 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

[2]. Bircher, B.A. et al., *CT machine geometry changes under thermal load*, Proceedings iCT - 9th Conference on Industrial Computed Tomography, 2019, https://www.ndt.net/article/ctc2019/papers/iCT2019_Full_paper_47.pdf

[3]. Obaton, A.-F., et al., *Reference standards for XCT measurements of additively manufactured parts*, iCT - 10th Conference on Industrial Computed Tomography, 2020, https://www.ndt.net/article/ctc2020/papers/ICT2020_paper_id152.pdf

[4]. Katic, M. et al., *Investigation of temperature-induced errors in XCT metrology*, International Journal of Automation Technology, https://doi.org/10.20965/ijat.2020.p0484

[5]. Biguri, A. et al., *Arbitrarily large iterative tomographic reconstruction on multiple GPUs using the TIGRE toolbox*, Journal of Parallel and Distributed Computing, https://arxiv.org/abs/1905.03748

[6]. Bircher, B.A. et al., *X-ray source tracking to compensate focal spot drifts for dimensional CT measurements*, Proceedings iCT - 10th Conference on Industrial Computed Tomography, 2020, https://www.ndt.net/article/ctc2020/papers/ICT2020_paper_id110.pdf

[7]. Bircher, B.A. et al., METAS-CT: *Metrological X-ray computed tomography at sub-micrometre precision*, Proceedings euspen's 20th International Conference & Exhibition 2020, https://www.euspen.eu/knowledge-base/ICE20131.pdf

[8]. Chrétien, S., et al., *Efficient hyper-parameter selection in total variation-penalised XCT reconstruction using Freund and Shapire's Hedge approach*, Mathematics, https://doi.org/10.3390/math8040493

[9]. Küng, A. et al., *Low-Cost 2D Index and Straightness Measurement System Based on a CMOS Image Sensor*, Sensors, https://www.mdpi.com/1424-8220/19/24/5461

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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