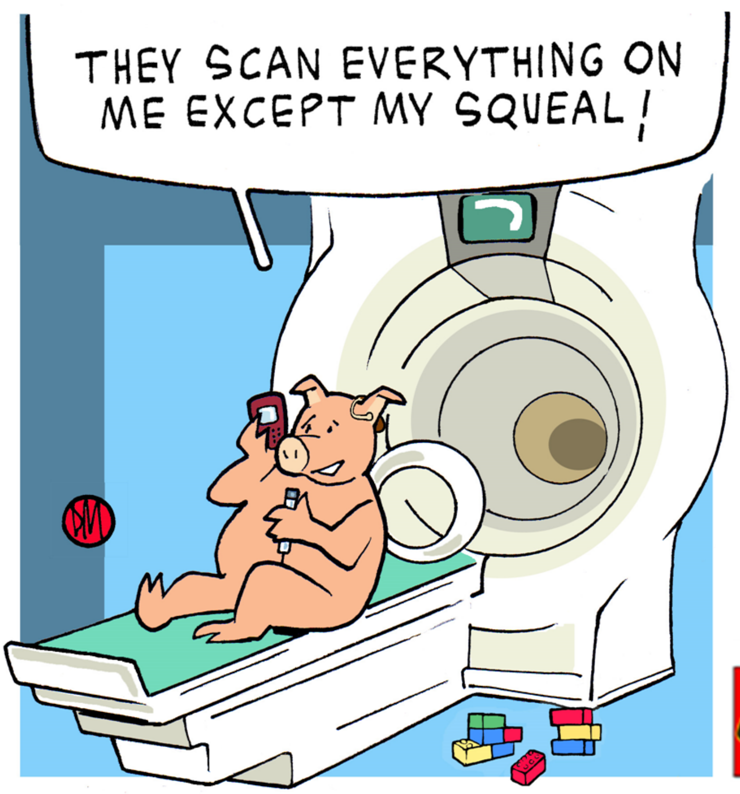
Centre for Industrial Application of CT scanning (CIA-CT) – Four years of results 2009-2013



L. De Chiffre, J.L. Andreasen, L.B. Christensen,
R.K. Feidenhans'l, B. Vinter, N.T. Jensen, M. Arentoft,
P.B. Jørgensen, M. Vester-Christensen, P.R. Schmidt

May 2014

Department of Mechanical Engineering

Technical University of Denmark

Abstract

The innovation consortium project, carried out September 2009 – August 2013, has aimed to help the participating companies and Danish industry with the introduction of CT scanning as measuring technology, carrying out research at international level. The project has operated through five main activities: Centre of Excellence, Dissemination, Collaboration, Research, and Initiation of new activities.

The consortium has consisted of nine partners, including three research institutions, two consultancy partners, two large companies, and two small / medium enterprises. The consortium has acted as a centre of excellence for industrial CT scanning, both nationally and internationally. A network with approx. 40 participants has been established, and a total of 22 students have been educated.

Dissemination activities have encompassed: a web page www.cia-ct.mek.dtu.dk , 8 newsletters, 4 topical conferences, 5 seminars and workshops, and 61 publications.

Collaboration has been established with a number of national and international actors in the field of CT, including societies and research organisations.

Five major research projects have been carried out: 1) CT scanning for coordinate metrology; 2) Data processing for high speed scanning; 3) New beam sources and signal conditioning; 4) Equipment with high stability beam source; 5) Quality assurance and automation.

A number of new activities have been initiated from the project, including participation in two new project proposals.

The project represents a major step forward towards the industrial application of CT scanning in Denmark.

Preface

This report briefly describes the main results achieved within the Danish project "Centre for Industrial Application of CT scanning - CIA-CT", an innovation consortium co-financed by the Danish Ministry of Science, Technology and Innovation during the period September 2009 – August 2013. The project was carried out by nine partners and coordinated by DTU Mechanical Engineering. Originally, there were nine partners in the consortium: DTU Mechanical Engineering, Computing Science Institute - University of Copenhagen, Niels Bohr Institute - University of Copenhagen, IPU, Danish Technological Institute, Novo Nordisk, Danish Meat Research Institute, Yxlon, and Deformalyze. During the project, Danish Meat Research Institute became a division under Danish Technological Institute (2009), Computing Science Institute became a division under Niels Bohr Institute (2010), Deformalyze reduced its activities (2011), and LEGO joined-in (2013).

The project teams were as follows:

- DTU Department of Mechanical Engineering, Manufacturing Engineering Division: Leonardo De Chiffre, Hans Nørgaard Hansen, Angela Cantatore, Jochen Hiller, Guido Tosello, Pavel Müller, Jais Angel, René Sobiecki, Peter Sanderhoff, and Jakob Rasmussen.
- Computing Science Institute - University of Copenhagen: Brian Vinter.
- Niels Bohr Institute - University of Copenhagen: Robert Krarup Feidenhans'l, Martin Beck, Torben H. Jensen, Torsten Lauridsen, Mikkel Schou Nielsen, Maria Thomsen, Kyriaki Glarina, Martin Rehr, and Jonas Bardino.
- IPU: Mogens Arentoft, and Erik Larsen.
- Danish Technological Institute: Niels Thestrup Jensen, Maria Holmberg, Peder Pedersen, Jens Bo Toftegaard, and Bo Nicolajsen.
- Novo Nordisk: Jan Lasson Andreasen, Bøje Meiner Gadegaard, Mette Poulsen, Niels Bjerrum Thomsen, Bente Eyving, Trine Sørensen, Charlotte Haagensen, Yongying Dai, Torben Ruby, and Lorenzo Carli.
- Danish Meat Research Institute: Peter Wagner, Lars Bager Christensen, Marchen Hviid, Paul Andreas Holger Dirac, Niels Christian Kjærsgaard, Claus Borggaard, Mikkel Engbo Jørgensen, and Eli Vibeke Olsen.
- Yxlon: Per Buchard Jørgensen, Jan Bressendorff, Jesper Irming Pedersen, and Andreas Taarning.
- Deformalyze: Martin Vester-Christensen and Søren Erbou.
- LEGO: Per René Schmidt, Pavel Müller, Stefania Gasparin, and Brian Hougaard Sørensen.

Leonardo De Chiffre
Professor, project coordinator

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1. Introduction

The "Centre for Industrial Application of CT scanning - CIA CT: Advanced 3D scanning for measurement, quality assurance and product development in industry" has focused on the industrial application of CT scanning for advanced 3D scan measurements, quality assurance and product development. The consortium has acted as a national competence centre in the industrial application of CT scanning and conducted research of benefit to the participating firms, the Danish industry and the Danish society.

The project has operated over 4 years (1st Sep. 2009 – 31st Aug. 2013) with a total budget of approx. 4M€.

2. CT scanning

X-ray computed tomography, called CT scanning in the project, is the method of using X-ray radiation to take a number of two dimensional images of an object in several positions around an axis of rotation and reconstructing a three dimensional model of the object's external as well as internal geometry.

The first CT scanner was built for medical imaging and since 1970 used in hospitals. Since 1980, CT scanning has been popular for material analysis and non-destructive testing (NDT). Since 2005, CT scanning has entered the application field of dimensional metrology, as the only technology being able to measure inside a component. CT scanning can be considered as a third revolutionary development in coordinate metrology, following the introduction of tactile CMMs in the seventies and that of optical 3D scanners in the eighties.

3. Project objectives

The project has aimed to help the participating companies and Danish industry with the introduction of CT scanning as measuring equipment and helped with research at international level. The project has operated through the following main activities:

- Centre of Excellence
- Dissemination
- Collaboration
- Research
- Initiation of new activities

The project is relevant for several industries: manufacturing, pharmaceuticals, electronics, food industry, construction industry and others, being also relevant for CT scanning applications in healthcare, security and others.

Together, it is estimated that the involved producing companies in the consortium and the interest group represent an annual turnover of approx. 30-40 billion €. The project has helped introducing the new technology as a tool for Danish industry and business, thereby reinforcing Danish competitiveness.

4. Centre of Excellence

The consortium has consisted of nine partners, including three research institutions (DTU Mekanik, eScience-NBI - University of Copenhagen, NBI Niels Bohr Institute - University of Copenhagen), two advisory partners (IPU, DTI Danish Technological Institute), one large company (Novo Nordisk) and two small / medium businesses (Yxlon, Deformalyze). During the project, Deformalyze has dropped-out and LEGO joined-in the consortium. Furthermore, DMRI Danish Meat Research Institute was a company when the project started, but became a part of DTI in 2009. Together with a number of national and international collaborators, the consortium has acted as a Centre of Excellence for industrial CT scanning, both nationally and internationally. A network has been established, and a number of students have been educated.

Figure 1: The kick-off meeting of the consortium took place at DTU on the 29th of September 2009. The nine partners were represented by 33 participants.

Besides taking part in the dissemination activities described in this report, 10 consortium meetings with internal exchange of information have been held at half-yearly intervals.

4.1. Network

A CIA-CT Network with approx. 40 participants was established, as illustrated in Figure 2. The network has followed the project through its dissemination activities.

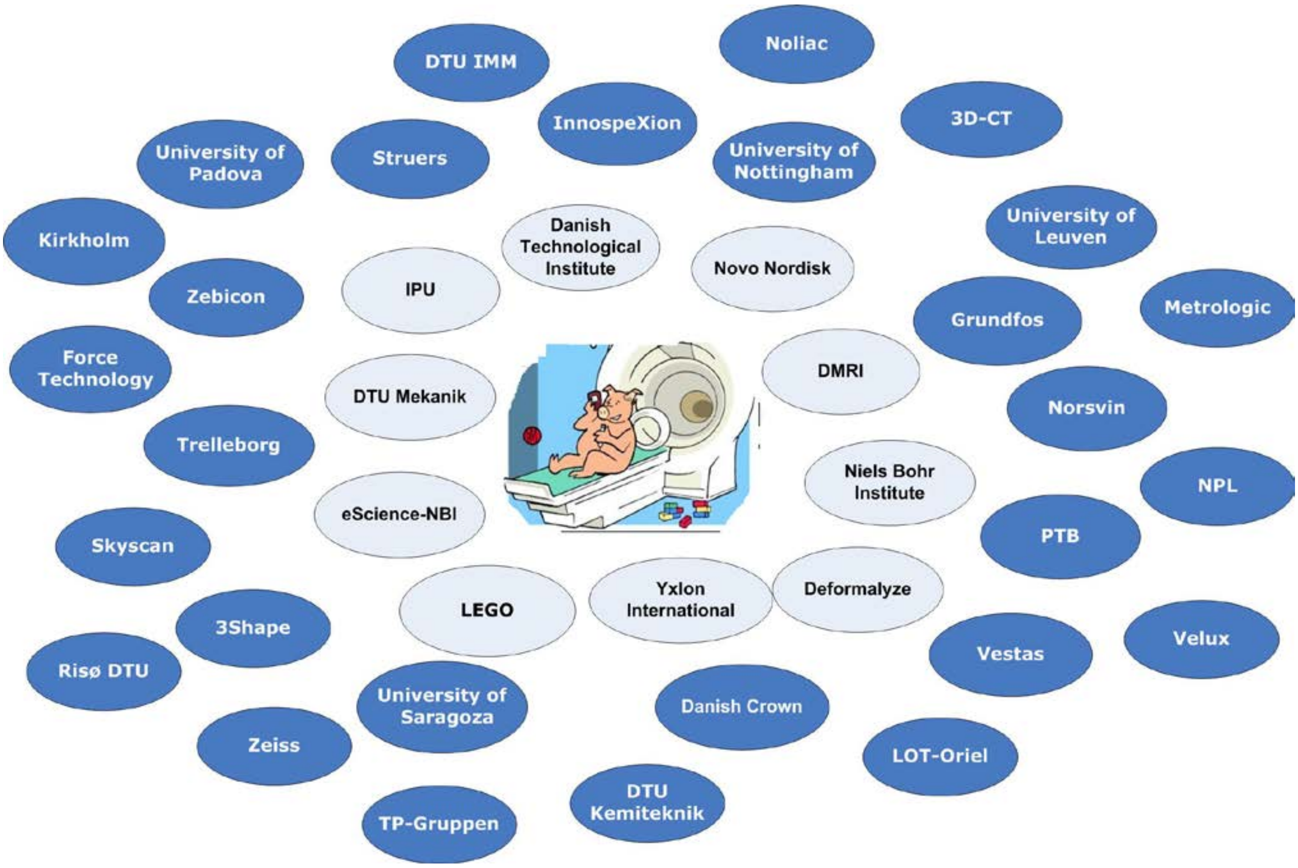

Figure 2: CIA-CT Network including Consortium partners.

4.2. Education

An important outcome from the centre has been the education of 14 Bachelor and Master students [MSc1-MSc14], and that of 5 PhD students [PhD1-PhD5] plus 3 in progress.

(Note: references are indicated using square brackets in the text and listed in section 10 of this report).

<u>Bachelor and Master students</u>
Maiken Stubkjær Schubert, DMRI and Copenhagen University, 2009.
Denis Dalla Fontana, DTU and UNIPD (Italy), 2010.
Karenina Arámbula, DTU and Monterrey Tech. (Mexico), 2010.
Riccardo Sauro, DTU and UNIPD (Italy), 2010.
Arvid Böttiger, NBI, 2010.

Louise Sperling, NBI, 2010.
Kenneth Malmstrøm Larsen, NBI, 2011.
Maria Thomsen, NBI, 2011.
Stefan Pedersen, NBI, 2011.
Mikkel Schou Nielsen, NBI, 2012.
Bjarke Hansen, NBI, 2012.
Yongying Dai, DTU, 2013.
Karin Ipsen, NBI, 2014.
Rasmus Laurberg Hansen, NBI, 2014.

Figure 3: Left: Karenina Arámbula, guest Master student at DTU from Monterrey Tech (Mexico), carries out experiments on CT scanner at DTI. Right: Riccardo Sauro, guest Master student at DTU from UNIPD (Italy), carries out experiments on CT scanner at Novo Nordisk.

<u>PhD students</u>
Martin Bech, NBI, 2009.
Torben H. Jensen, NBI, 2010.
Ramona Pacurar, DTU and TUCN (Romania), 2011.
Pavel Müller, DTU, 2012.
Jais Angel, DTU, 2014.
Torsten Lauridsen, NBI, on going.
Mikkel Schou Nielsen, NBI, on going.
Maria Thomsen, NBI, on going.

Figure 4: Pavel Müller defended his PhD at DTU on Friday, March 8th, 2013. From left, the appointed examiners Assistant Professor Simone Carmignato, Univ. of Padova, Professor Jean-Pierre G. Kruth, Univ. of Leuven, and Associate Professor Giuliano Bissacco, DTU, Associate Professor Guido Tosello, DTU who chaired the defense, Prof. Leonardo De Chiffre, DTU, main supervisor, and Dr Pavel Müller, DTU.

5. Dissemination

Project dissemination has encompassed:

- Newsletter
- Web page
- Seminars
- Publications

5.1. Newsletter

A half-yearly newsletter was distributed to the members of the CIA-CT network and other interested people. The newsletters can also be downloaded from the CIA-CT web page.

CIA-CT

Project Newsletter
June 2013 - NR 8

Center for Industrial Application of CT scanning

EDITORS' NOTE

Dear reader, welcome to the eighth issue of our six monthly newsletters from the CIA-CT project! The eighth consortium meeting which took place at DTI on March 12, 2013 and the new Inter laboratory comparison on Industrial Computed Tomography are relevant events that took place during the last six months. In particular, the comparison involving 27 participants worldwide has been successfully carried out and its preliminary results will be presented and discussed at a workshop at DTU on June 20, 2013. In this issue we present LEGO that in 2013 has joined the CIA-CT as a new project partner. We also recall the 4th CIA-CT Conference on "Applications of Computed Tomography in Industrial Production" that will be held at the University of Copenhagen on June 19th, 2013. The detailed program is presented at the end of this newsletter.

We hope that you will enjoy reading.

With greetings,

The Editor

www.cia-ct.mek.dtu.dk NR 8/2013

Figure 5: CIA-CT Project Newsletter no. 8/2013 [New8].

5.2. Web page

A web page was created from the project start at www.cia-ct.mek.dtu.dk. The web page is still operating and will be used for information on relevant activities over the following years.

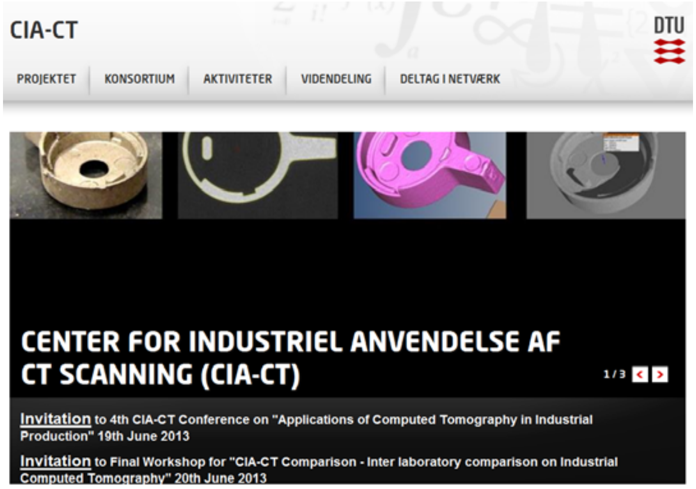

Figure 6: Screenshot of CIA-CT webpage.

5.3. Seminars

Four yearly conferences were organized, with approx. 60 attendees each. A total of 5 seminars and workshops were held. Furthermore, 16 presentations were held at national and international conferences. For details, please see section 10 Publications in this report and the CIA-CT web page for programs, photos, etc.

Figure 7: 1st CIA-CT Conference on "Application of CT scanning in industry", DTU, June 8, 2010 [Con1].

5.4. Publications

The centre has produced a considerable amount of scientific publications (for details, please see section 10):

- 5 PhD theses (+ 3 upcoming) [PhD1-PhD5].
- 14 MSc theses [MSc1-MSc14].
- 17 Journal papers [PJ1-PJ17].
- 14 Papers in Proceedings [PC1-PC14].

6. Collaboration

Partners in the CIA-CT consortium have established fruitful collaboration with organisations and research organisations, both nationally and internationally.

International organisations:

- International Academy for Production Engineering (CIRP),
- European Society for Precision Engineering and Nanotechnology (euspen).

National organisations:

- FVM – Industriel Metrologi (Danish Society for Engineering Metrology).

Universities and National Institutes:

- University of Padova, Italy
- KU Leuven, Belgium
- Physikalisch-Technische Bundesanstalt (PTB), Germany
- National Physical Laboratory (NPL), UK
- University of Applied Sciences Upper Austria, Austria.

<u>Stay abroad</u>

PhD student Torben H. Jensen (NBI), PSI Paul Scherrer Institute, Villigen, Switzerland, 2.5 Months.
PhD student Torsten Lauridsen (NBI), ESRF European Synchrotron Radiation Facility, Grenoble, France, Sep. - Oct. 2011.
Dr Angela Cantatore (DTU), PTB Braunschweig, Germany, Sep. - Dec. 2011.
PhD student Pavel Müller (DTU), PTB Braunschweig, Germany, May - June 2012.
PhD student Jais Angel (DTU), KU Leuven, Belgium, Sep. - Dec. 2012.
PhD student Mikkel Schou Nielsen (NBI), PSI Paul Scherrer Institute, Villigen, Switzerland, Aug. - Dec. 2013.

7. Research

Five major research projects have been carried out within CIA-CT:

1. CT scanning for coordinate metrology;
2. Data processing for high speed scanning;
3. New beam sources and signal conditioning;
4. Equipment with high stability beam source;
5. Quality assurance and automation.

The five work packages (WP) are illustrated in Figure 8 and briefly described in the following.

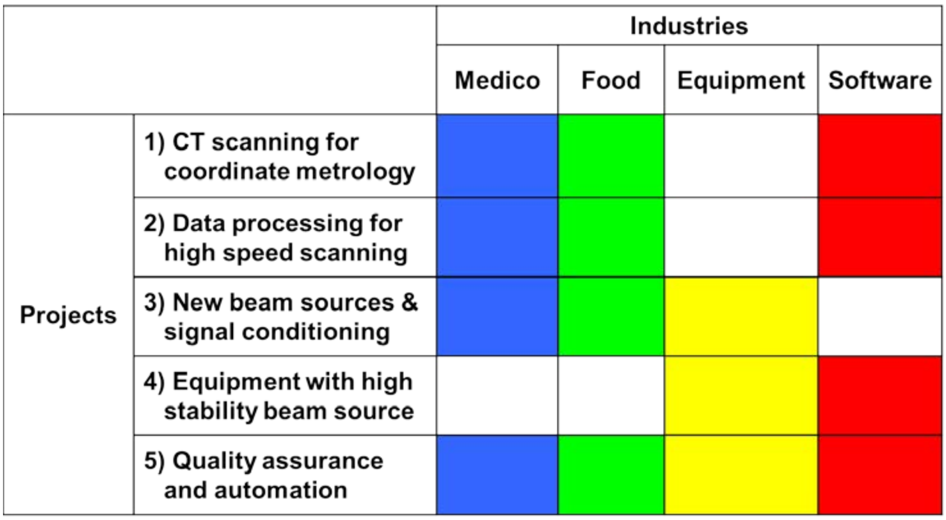

Figure 8: Research projects within the CIA-CT with indication of involved industrial partners.

<u>WP1 - CT scanning for coordinate metrology (WP manager: DTU)</u>

Objectives

Objective of this WP has been to develop methods, equipment and reference standards to achieve traceable coordinate measurements using CT scanning.

WP1 has consisted of the following tasks:

Task 1.I	Influence factors
Task 1.II	Sensitivity analysis
Task 1.III	Mathematical modelling
Task 1.IV	Procedure development
Task 1.V	Equipment development
Task 1.VI	Calibration artefacts
Task 1.VII	Calibration methods
Task 1.VIII	Uncertainty budgets

X-ray computed tomography (CT) is a measuring technique which has become an important technology in the production environment over the last years. Due to a number of advantages of CT compared to, e.g., coordinate measuring machines (CMMs), CT has been recently spread in the field of manufacturing metrology and coordinate metrology and is currently becoming a more and more important measuring technique for dimensional measurements. This is mainly due to the fact that, with CT, a complete three-dimensional model of the scanned part is in a relatively short time visualized using a computer, and measurements of outer as well as inner geometries can be performed with micrometer resolution. A flow chart of a typical dimensional CT measurement process is shown in Figure 9.

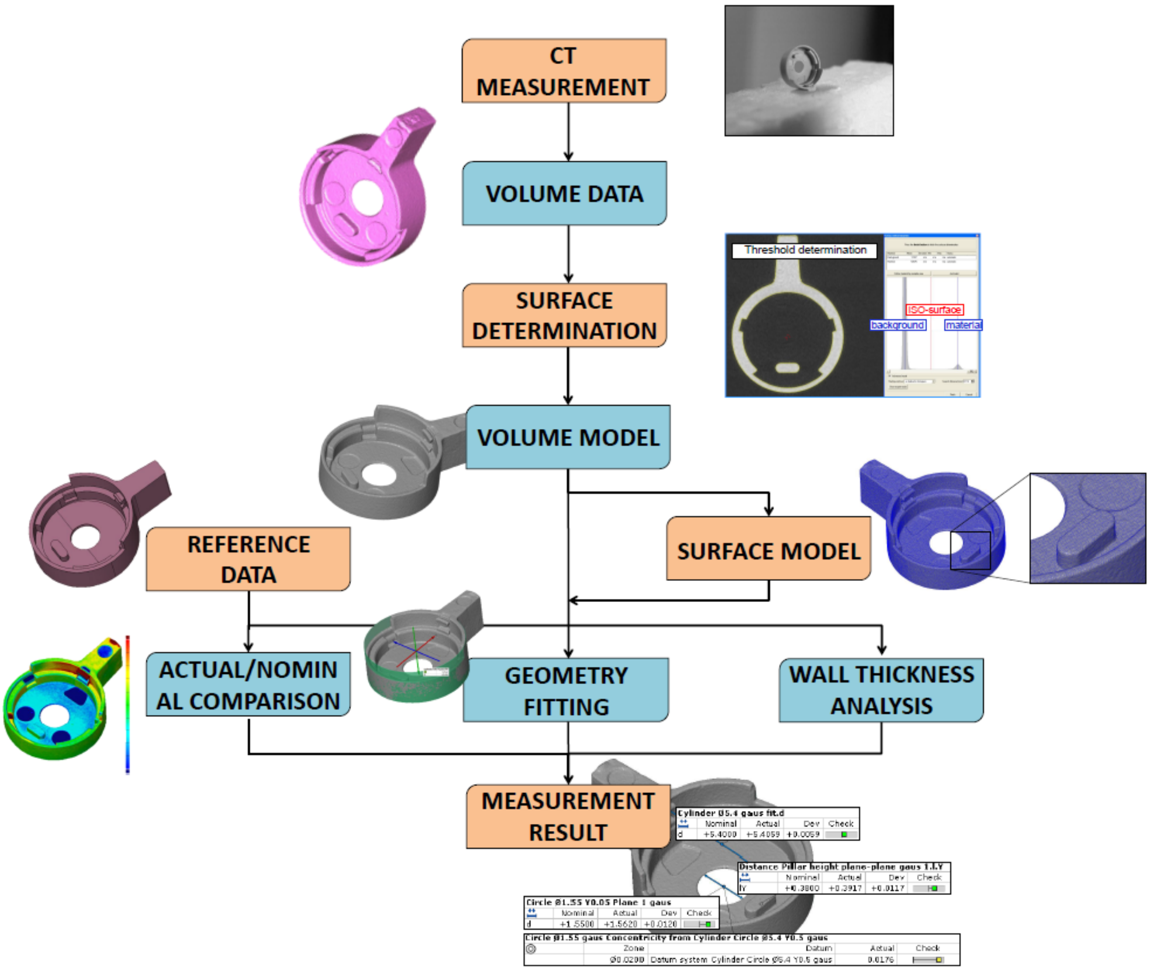

Figure 9: Flow chart of a typical dimensional CT measurement process [PhD4].

The result of dimensional CT measurements, as of every other measuring instrument, has to be accompanied with a statement about the measurement uncertainty. The knowledge about measurement uncertainty is an important factor for decision making about manufactured parts. However, due to many influences in CT, estimation of the uncertainty is a challenge, also because standardized procedures and guidelines are not yet available.

In this WP, several methods for uncertainty estimation were applied in connection with a number of industrial components as well as calibrated workpieces. Measurement uncertainty was often used as a parameter for quantification of a selected influence quantity. Uncertainty estimation using the substitution method appeared to be well applicable to CT measurements in production environment. By performing repeated measurements of the calibrated workpiece, characterization of a CT system under study for a specific task part was achieved. The task-specific measurement uncertainty from repeated measurements was then transferred to other uncalibrated workpieces. It was documented that CT is a well-established technique for tolerance verification of manufactured parts.

Five reference objects for performance characterization of industrial CT systems were developed within the scope of this WP. Namely, CT ball plate, CT tree, step gauge, step cylinder, and a cylindrical multi-material assembly (see Figure 10), which were further used for identification, characterization and correction of measurement errors in the CT volume. Their application appeared to be suitable for this task. Because the five objects consist of ruby spheres, carbon fibre and polymers, CT scans do not produce image artifacts, and evaluation of distances is robust. The role of material and form errors present in industrial parts was investigated in another work package (WP5). Setup example of the CT ball plate in a CT scanner is shown in Figure 11.

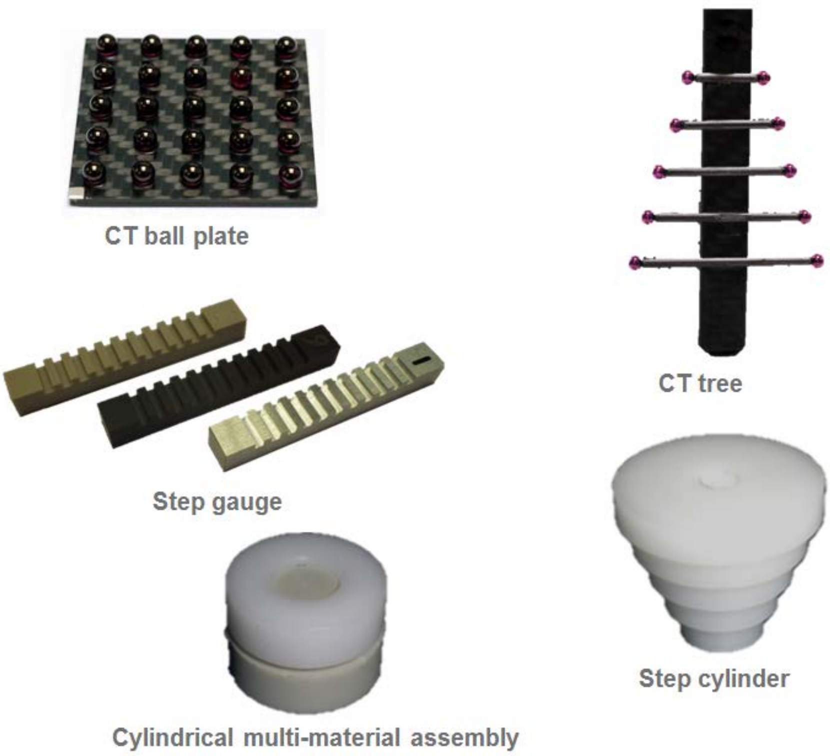

Figure 10: Five reference objects for performance characterization of industrial CT systems developed at DTU [PhD4, PhD5].

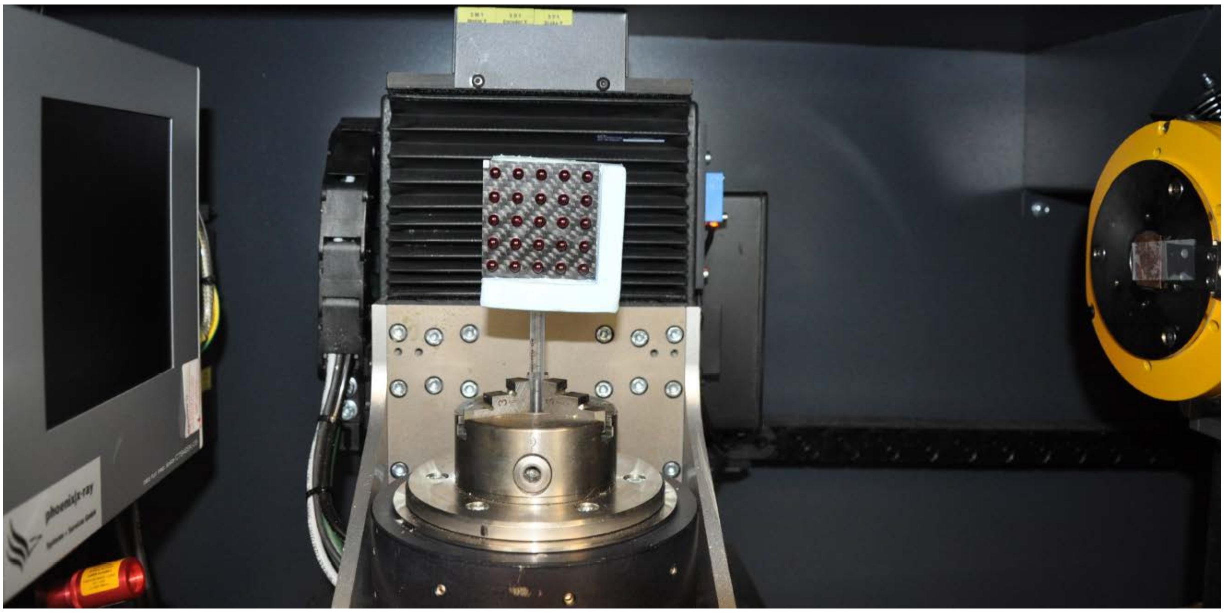

Figure 11: Setup of CT ball plate in CT scanner [PhD4].

Several methods for scale error correction were implemented to correct original reconstructed volume data sets. E.g. this was done using the CT ball plate, the CT tree, the calibrated features measured by CMM and the ”data base” approach considering a previous characterization of the CT system with a number of CT measurements using a calibrated ball bar. As, for example, methods using the two reference objects consisting of spheres, is a classical way for correction of the voxel size, by comparing the distance between centres of spheres measured by CT to calibrated values, the application of calibrated features was documented on a metallic as well as on a plastic part and resulted in comparable observations. The method using the ”data base” approach seemed to work well, but its applicability shall be further validated.

Seven synthetic volume phantoms were developed by DMRI for the meat industry, to be used instead of real pig carcasses. A volume phantom consists of several polymer components, such as polymethylmethacrylate (PMMA), polyethylene (PE) and polyvinylchloride (PVC), see Figure 12. The volume phantoms were further used for identification, characterization and correction of volume measurement errors in a clinical CT. Because the volume phantoms consist of polymers, CT scans does not produce image artifacts, and evaluation of volumes is robust. Calibrations were performed using the pycnometer method, based on water displacement, to determine the reference volume of all materials in the set of volume phantoms before assembly. The phantoms were used for performance characterization of clinical CT systems under another work package (WP5). Their further application in WP5 appeared to be suitable.

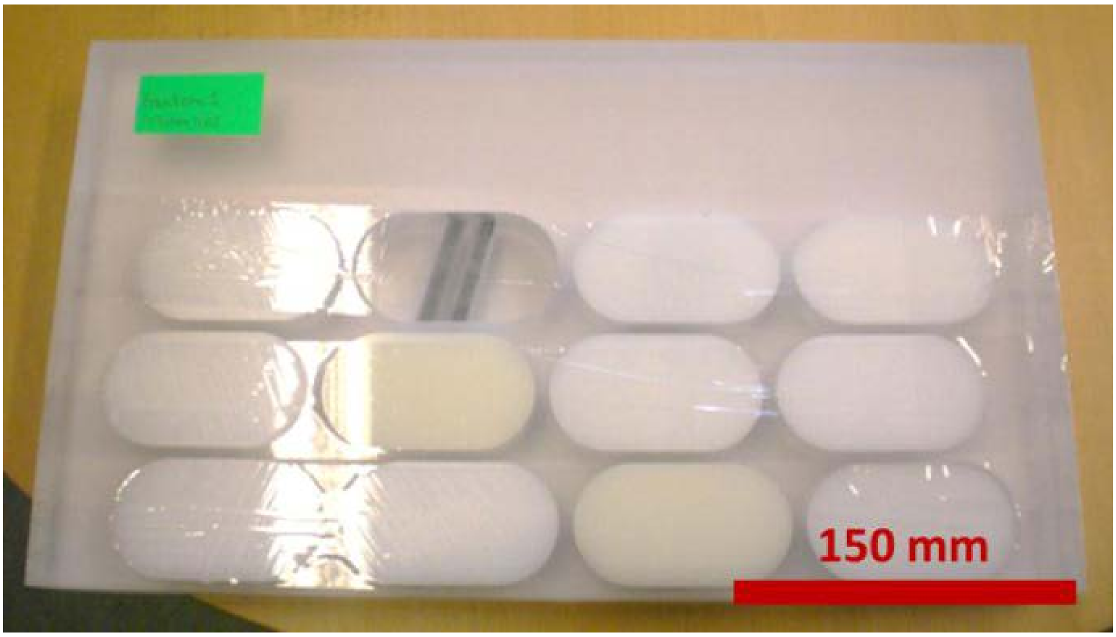

Figure 12: Synthetic volume phantom for performance characterization of clinical CT systems developed at DMRI [PhD5].

A half carcass phantom (Figure 13) was developed for fat determination of meat end products. The scope of this phantom is for identification, characterization and correction of geometrical measurement errors in a clinical CT. The phantom includes several free form surfaces creating a challenge to the calibration system and methodology. Such details have to be included to represent vital dimensions of the real carcass, dimensions that must be determined using automated software algorithms.

Figure 13: Half carcass phantom for performance characterization of clinical CT systems developed at DMRI and calibrated at DTU Mekanik (left), and thereafter scanned in a CT (right) [PC13].

WP2 - Data processing for high speed scanning (WP manager: DIKU)

Objectives
Objective of this WP has been to develop methods for processing and post-processing of data from CT scanning.

WP2 has consisted of the following tasks:
Task 2.I Two target domains for prototyping
Task 2.II Target performance
Task 2.III Development framework
Task 2.IV Example algorithms
Task 2.V Example one
Task 2.VI Example two
Task 2.VII Result analyses

eScience-KU has been working on methods to simulate CT scanners to enable what-if testing of scanner designs before building the scanner, and testing the realtime performance one may obtain for industrial CT applications. One case is focused on developing and building a solution for efficient analysis and cutting of pork carcasses in slaughterhouses. The analysis is based on CT scanning and online reconstruction of the intersection images in the actual production line, so the results must be available within seconds in order to keep up with the production flow. As an example the meat intersection image in Figure 14 could result in detector readings as visualized in the sinogram, and we can then use e.g. filtered back projection to reconstruct an estimate of the actual intersection.

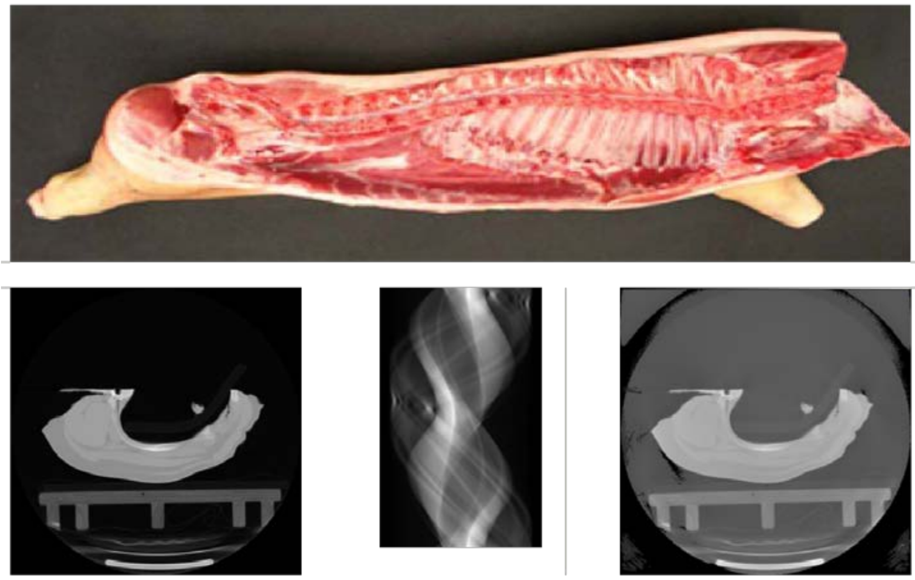

Figure 14: Half a pork carcass (top), intersection of similar meat lying on a conveyor belt (left), the resulting scanning sinogram (center) and the reconstructed image (right) [New4].

The case requires very high continuous usage of the CT scanner. Thus a number of design choices for the scanner had to be tested. The first technical task at KU was to provide inputs for the scanner setup decisions. Firstly, a grid enabled web portal providing interactive image reconstruction with variable source count and position was implemented (excerpt in Figure 15). Using the portal the project participants could easily investigate the image quality and thus the feasibility of various stationary source solutions.

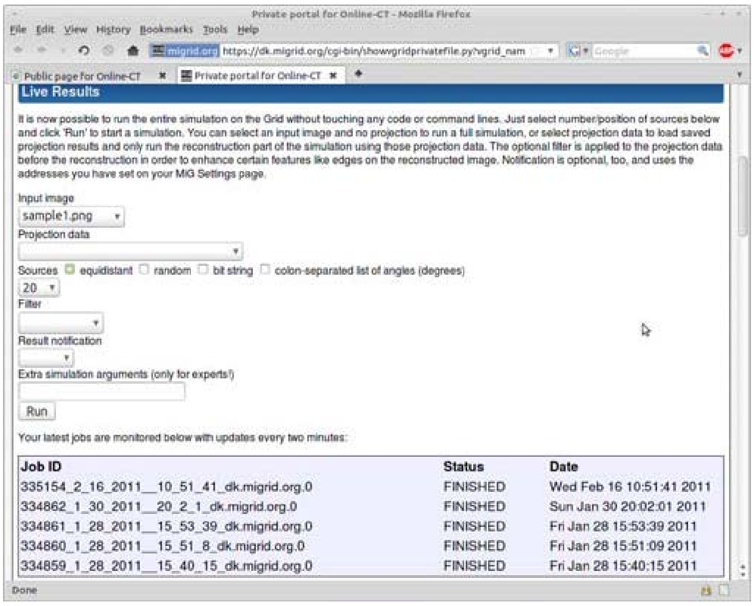

Figure 15: Web portal with live image reconstruction [New4].

The different simulated scans can then be passed to both quantitative and qualitative quality analysis. In KU experiments, the move from step and shoot fan beam to spiral cone beam CT removed a lot of mechanical challenges but instead introduced a huge amount of extra computation required in the already short period available in the production line. Thus the idea of using limited parallel optimization requirements had to be refined.

eScience-KU group has started to investigate spiral cone beam reconstruction implementations and the optimizations needed for the short time frame. It still seems to be possible to build a fitting solution using state of the art GPU hardware and a highly optimized implementation of the reconstruction algorithms but this target is still away from the required performance.

The group is currently working closely with the project engineers in building a working prototype of the scanner and showing that it is actually possible to reconstruct usable images albeit in a longer time frame. Once achieving this target, attention will be focused to image reconstruction performance and to integration with the further image analysis tools on the way from image to the cutting machine. The simulation environment, and the hundreds of CPUs that powers it, provides for a very convenient platform for testing CT scanner designs. In the future more reconstruction algorithms will be supported and a number of filters for the reconstructed images will be offered as well.

WP3 - New beam sources and signal conditioning (WP manager: NBI)

Objectives
To develop and implement a new lab based CT scanning technique for phase contrast imaging.

The following tasks have been accomplished
Task 3.I Setup of phase contrast instrument at NBI
Task 3.II Implement procedures for stable data acquisition and stable operation
Task 3.III Implementation of dark field imaging
Task 3.IV Test measurements on meat samples and comparison with SR data
Task 3.V Test to see contrast between meat and cartilage
Task 3.VI Comparison between normal CT, phase contrast and dark field imaging on meat samples
Task 3.VII Investigate possibility for further collaboration

A grating based interferometer X-ray phase-contrast (GIXF) setup (Figure 16) has been added at the existing Rigaku rotating anode at HCØ at University of Copenhagen. The setup is running at 50 kV and 200 mA. The first image of a Legoman is shown in Figure 17. Images and tomograms are now been routinely obtained, but there was a major breakdown of the anode just after the end of CIA-CT. However, the setup up runs again with a visibility of about 13 % in the fringes. This could probably be improved with new and optimized gratings. Currently the setup uses either to the 3rd or the 5th fractional Talbot distance for various applications. The application area is normally within food science although other sample types are also tested.

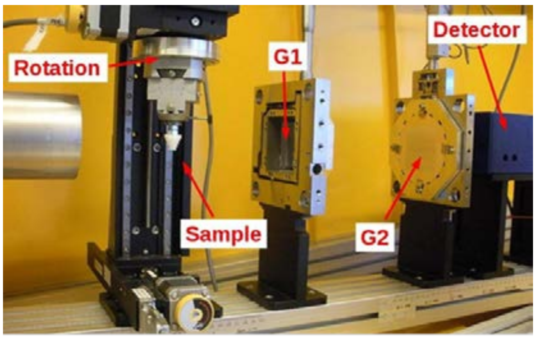

Figure 16: X-ray setup at NBI. The gratings are to the right.

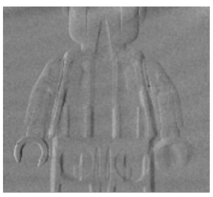

Figure 17: Phase contrast image of a LEGO man [Con4].

Both phase contrast and dark-field imaging have been implemented and the results have been obtained and are published in the journal Food Control [PJ11]. The focus so far has been on foreign body detection in food products where dark-field imaging shows great potential as a complementary imaging modality to conventional absorption contrast imaging. The first data set was part of Mikkel Schou Nielsen's MSc thesis [MSc10] and showed the potential of the technique for foreign body detection. The second article shows the potential of the dark field technique for detecting frost damages in berries and fruit. Apparently frost damages in berries causes cell damages that are visible in dark field imaging, but not in normal absorption mode. This effect will be investigated further in the future and might be used for applications. In the spring of 2012, a project on using new X-ray imaging modalities, in particular absorption and dark-field imaging, for quality assessment of chocolate products was performed in collaboration with the company TOMs (see application example in Figure 18). Today, the quality assurance for monitoring of the correct filling in chocolate plates is cumbersome. The aim of the investigation was to see if X-ray imaging could be used to measure the content of filling in a chocolate plate.

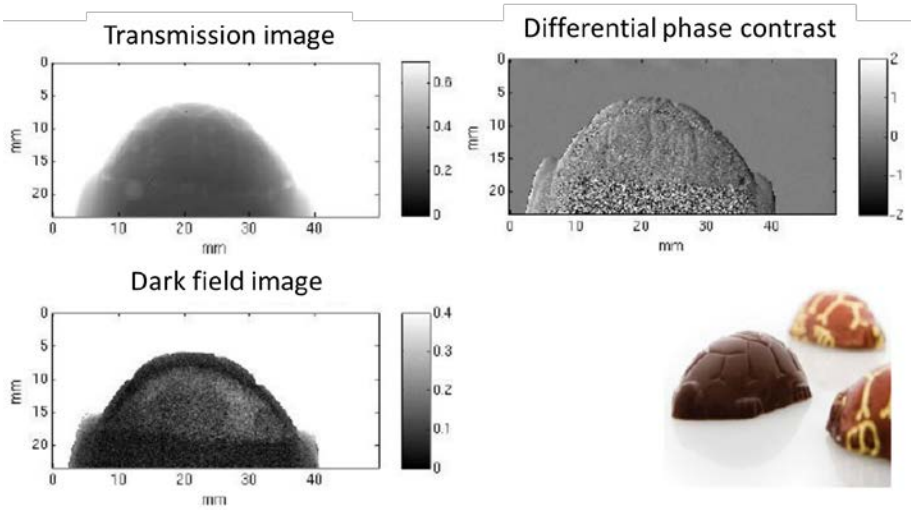

Figure 18: Radiograms of a "Toms skildpadde" chocolate with filling using absorption- (upper left), refraction- (upper right) and scattering-based contrast. The contrast between filling and chocolate is largest using the scattering contrast [New6].

Dark field imaging has also been tested in a metrological study in a collaboration between NBI and DTU and a publication has been accepted. A range of new applications of dark field imaging in materials science are being pursued. A paper has been accepted in Applied Physics A showing how dark field imaging can be used to map misorientations of fibers [PJ16]. This could be of interest in fiber enforced materials. The techniques can also be used for mapping of very small cracks that are invisible by absorption based methods when the cracks are of size below the pixel size of the tomograms. Two more articles using this approach are under preparation. Besides the laboratory work, analysis of X-ray data measured on a grating based set up at Technische Universität München (TUM) has been done. We measured on beef samples from DMRI. The original purpose was to investigate if it was possible to detect differences in beef tenderness from the dark field or electron density tomograms obtained by the setup. We have not yet been able to distinguish beef quality from our data, but the data analysis has led to the creation of 2D (electron density, absorption length) histograms (Figure 19) of the tomogram data. These tomograms represent an X-ray refractive index distribution, and can be expanded to 3D by incorporating the incoherent scattering length from the dark field tomograms. In total this 3D distribution gives a unique and new overview of the optical characteristics of a given sample. The method has been published in Phys.Med.Biol. (2012).

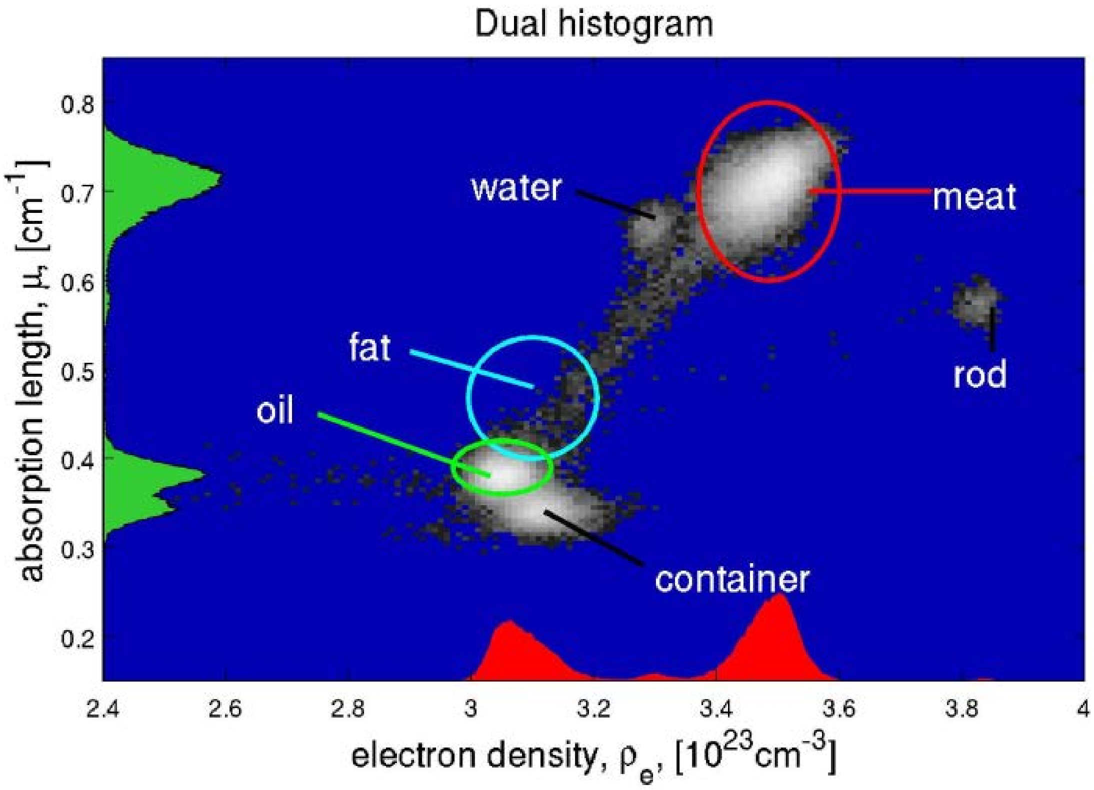

Figure 19: Dual Histogram of absorption and phase contrast data.

In July of 2012 in collaboration with a research group at LIFE, CT-measurements on meat samples were performed at a synchrotron facility. The samples were emulsions of protein and fat used for sausages. The aim of the measurement was preliminary investigations of what information CT-measurements can give on heterogeneous meat products, and to evaluate if new imaging modalities can provide added contrast and better signal quality than conventional CT. As seen in Figure 20, preliminary studies show that there are clear improvement in SNR and CNR when using phase-contrast CT measurements for studying meat products.

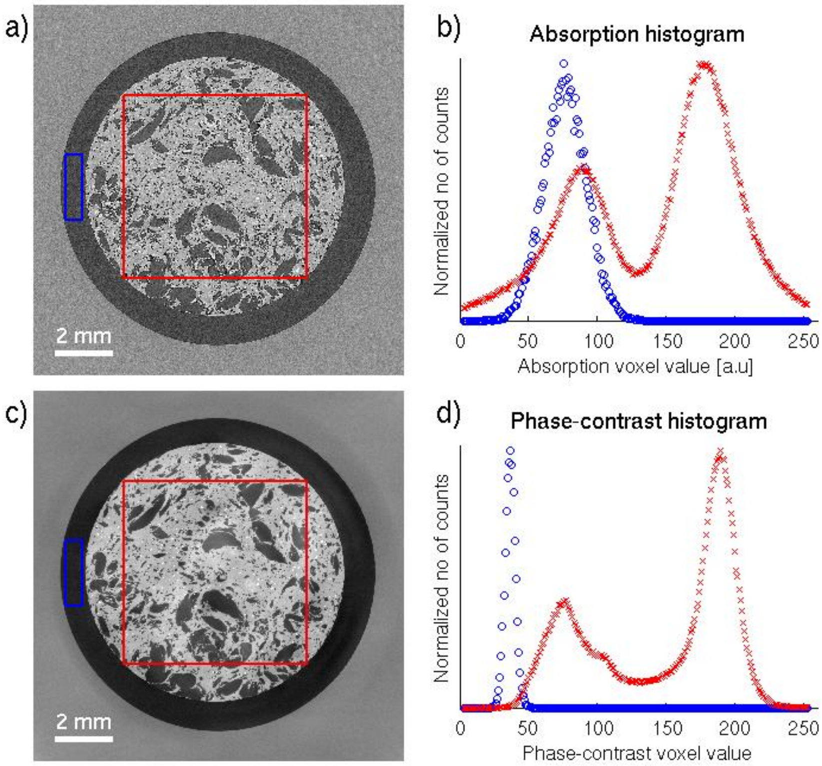

Figure 20: Absorption (top) and phase-contrast (bottom) CT measurements show that the phase-contrast CT has a superior SNR and CNR between the fat and protein. The blue graph in the histograms (right) which show the distribution of voxel values of the Eppendorf tube and the red graph of the meat sample confirm this.

Work is currently including development of new methods for image processing of meat samples and two publications are under preparation. Experiments with Insulin injections in pork meat simulation in injections in human tissue have also been performed in collaboration with Novo Nordisk. The aim is to investigate the shape of the insulin depot after injection and how it influences the effect of the injection. Measurements have mostly been performed in absorption mode using Iodine as a contrast agent. Examples are shown in Figure 21.

Figure 21: Two different insulin depots after injection in pork meat [MSc8].

Experiments have been performed on pork fat and published in Meat science. Phase contrast measurements give a significant better contrast. Enhancing between meat and cartilage the contrast sufficiently to discriminate the two has not yet been successful. In collaboration with the Department of Oral & Maxillofacial Surgery, Institute of Odontology, Faculty of Health Sciences, University of Copenhagen a novel approach to analysis of bone integration for dental implants has been tested. The method uses 3D tomograms rather than the 2D cross sections investigated using light microscopes that are traditionally used for evaluation. The method gives an overall picture of the radial dependencies of some key parameters (bone fraction, bone density) for the whole volume surrounding the implant. A paper is being prepared for submission. The CIA-CT project has given us a perfect platform to develop the grating based technique and apply for new funding. Funding from the strategic research council has been granted for a project entitled NEXIM: New X-ray Imaging Modalities - For Safe and High Quality Food. The project is a collaboration between the Niels Bohr Institute and the Department of Food Science at KU, Danish Meat Research Institute at TI and Department of Informatics and Mathematical Modelling at DTU. We have also made close contacts with a range of companies and Institutes that we are now collaborating with. Furthermore we are participating in the p3 project funded by Højteknologifonden and the CINeMA project funded by the strategic research council.

WP4 - Equipment with high stability beam source (WP manager: IPU)

Objectives
To define, improve and verify the beam stability.

The following tasks have been accomplished

Task 4.I	Mapping of stability
Task 4.II	Minimisation of short term instability (ripples)
Task 4.III	Minimisation of long term instability (drift)
Task 4.IV	Evaluation of improvements
Task 4.V	Measurement of 3-4 test pieces
Task 4.VI	Verification/Industrial validation

The grating interferometer from WP3 was tested with respect to stabilities. As the grating was stepped with submicron precision, stability was a key issue. It turned out that the instabilities mainly were coming from temperature variations. After careful stabilization of the room temperature, the fluctuations were much reduced.

The task of correcting instabilities in the grating interferometer setup at the NBI (developed in WP3) was solved using two different approaches. The first approach was the straight forward work to minimize the mechanical instabilities of the setup. The major contribution to the mechanical instability was due to air conditioning effects. A new control unit greatly minimized the mechanical instability reflecting in significantly reduced time variations in measurements. The second approach was a computational data analysis approach.

Rather than assuming perfectly constant mechanical circumstances, which will in reality never be the case, a new algorithm for grating interferometer data analysis was developed.

Yxlon established a test unit for measuring the long term stability of the beam using dedicated software and several kinds of external detectors. The stability was measured for CT scanners available at Novo Nordisk and DTI. Some variations were identified and analyzed by NBI with the purpose of software compensation. No systematic variations could be identified, and a numerical elimination or compensation for the variations was therefore not possible. In Figure 22, the Novo Nordisk CT scanner and the variations in dose are shown as an example.

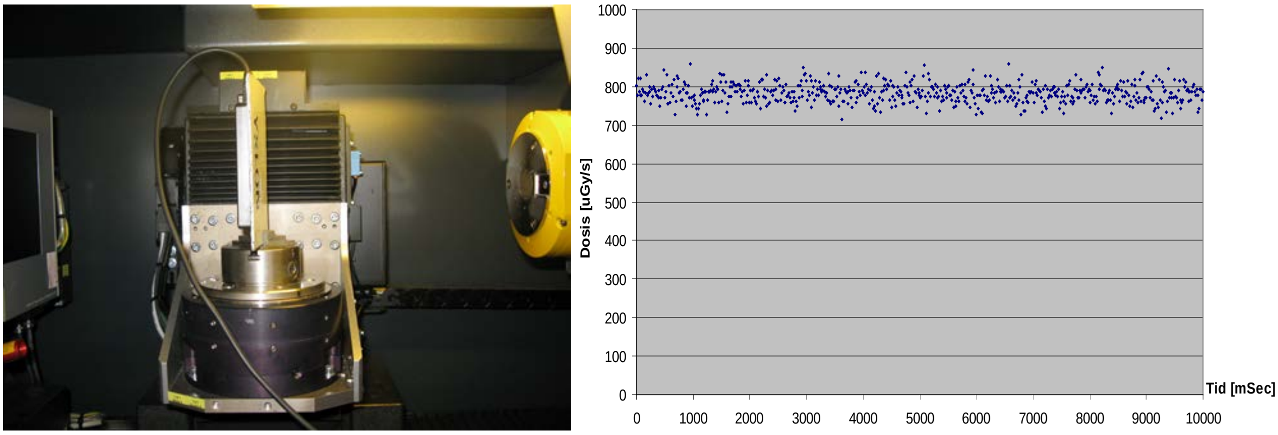

Figure 22: Stability test. Position of detector in scanner (left) and typical results (right).

Since commercial CT-scanners take variations into account by repeating the measurements and average over time and position on detector, there is no clear influence on the quality of measurements carried out on the tested scanners.

Besides the test unit, Yxlon has during the entire project worked on an improved power supply for the system. The power supply is more stable and is expected to be a part of future products from Yxlon.

WP5 - Quality assurance and automation (WP manager: DTI)

Objectives

Objective of this WP has been to develop methods and software for use of CT in production environments in the industry, as automatic tool for ensuring and measuring quality in an industrial manufacturing process. This project is expected to deliver a series of algorithms and software solutions, for automatic verification of dimensions tolerances and geometrical tolerances on as well macro as on micro level. In 2011, the company Deformalyze withdrew from the project, and thus competences within algorithms and software in the WP was highly reduced and it had an influence on the work carried out in 2012 and 2013.

WP5 has consisted of the following tasks:

Task 5.I Assembly inspection
Task 5.II Quality of components
Task 5.III Tolerance verification
Task 5.IV High resolution investigation on meat products
Task 5.V Proficiency testing on medical samples
Task 5.VI Proficiency testing on meat samples
Task 5.VII Pig body quality inspection
Task 5.VIII Pig body partition
Task 5.IX Pig fat determination
Task 5.X Demonstrator for medical industry
Task 5.XI Demonstrator for meat industry
Task 5.XII Demonstrator for toy industry

A series of cylindrical multi-material assemblies as well as a step cylinder were tested for assembly inspection and X-ray contrast modality using a grating interferometer for metrological issues at NBI. Both the reconstruction of the 2D X-ray images and data analysis of the tomograms were performed using VolumeGraphics software (VG StudioMax). Furthermore, image analysis on profile plots and gradient plots were performed on single projections using SPIP 5.1.5. Results show that segmentation is possible but further development related to stability issues on the used CT scanner is needed to achieve a metrological tool using x-ray contrast modality. Single projection images are shown in Figure 23 for an assembly of two different materials with same density.

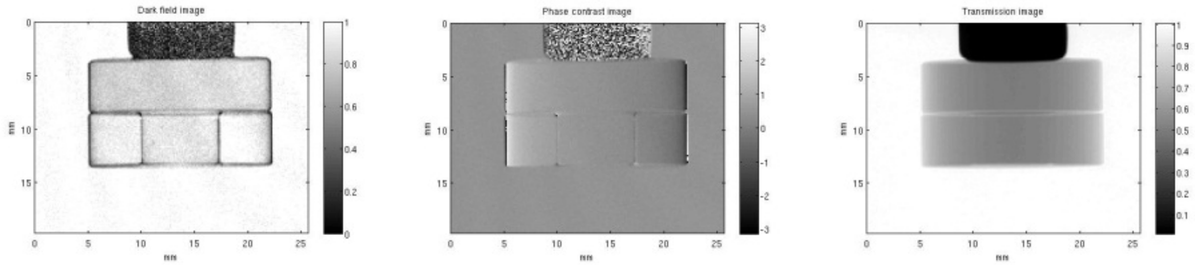

Figure 23: Single projection images for an assembly of two different materials with same density [PhD5]. Left: Dark field image. Middle: Phase contrast image. Right: Transmission image.

An interlaboratory comparison on industrial X-ray Computed Tomography was organized by DTU [Rep6]. 27 laboratories from 8 countries were involved in the comparison, see Table 1, and CT scanned two items selected among common industrial parts: a polymer part and a metal part (Figure 24). The two items are considered more similar to industrial parts commonly measured in industry, in terms of material, dimensions and geometrical properties, than reference artefacts commonly used for calibration and verification of CT scanners. Different measurands are considered, encompassing diameters, roundness, and lengths. All single items were measured by the coordinator using coordinate measuring machines before and after circulation. Both the metal item and the plastic item have shown a good stability over the total period of approx. 6 months. Depending on item and measurand, reference expanded uncertainties (k=2) ranging from approx. 1.5 µm up to approx. 5.5 µm were estimated. Out of a total of 167 results obtained by the participants using CT scanning, 54% of the measurements yield $|E_n|$ values less than 1 and 46% larger than 1, where $|E_n| < 1$ indicates agreement between measurement results while $|E_n| \geq 1$ shows disagreement. The comparison has shown that CT measurements on the industrial parts used lie in the range 6-53 µm, with maximum values up to 158 µm, compared to average uncertainties below 5.5 µm using CMMs.

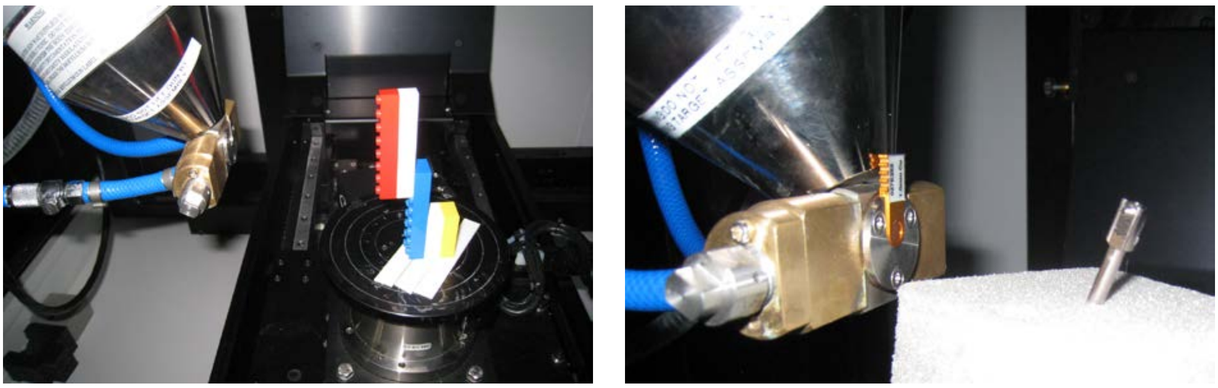

Figure 24: The measurement set-up and fixture for the two items used in the CIA-CT interlaboratory comparison of industrial CT scanners: plastic Lego brick (left) and metal part (right) from a medical device [PJ14].

Table 1: List of participants in the CIA-CT comparison of industrial CT scanners [Rep6].

Participant	Country
3D-CT A/S	Denmark
BAM Federal institute for materials research and testing	Germany
Braun GmbH, Precision Measurement , CAQ-Engineering	Germany
Carl Zeiss IMT GmbH	Germany
Danish Technological Institute (DTI)	Denmark
Fraunhofer Development Center for X-ray Technology (EZRT)	Germany
GE Measurement & Control (Zebicon A/S)	Denmark
GRUNDFOS A/S	Denmark
Hexagon Metrology Inc	USA
Huddersfield University (HUD)	UK
Institute of Manufact. Metrology, Friedrich-Alexander-University Erlangen-Nuremberg (FMT)	Germany
Katholieke Universiteit Leuven	Belgium
LEGO System A/S	Denmark
National Metrology Inst. of Japan, National Inst. of Advanced Ind. Sci. and Technology (AIST)	Japan
National Physical Laboratory (NPL)	UK
Nikon Metrology UK	UK
Novo Nordisk A/S, Device R&D	Denmark
Novo Nordisk A/S, DMS Metrology & Calibration	Denmark
SGS Institut Fregenius GmbH	Germany
SIMTech	Singapore
UNCC, Center for Precision Metrology	USA
University of Padova (UNIPD)	Italy
University of Southampton	UK
Wenzel Volumetrik GmbH	Germany
Werth Messtechnik GmbH	Germany
Mikroproduktionstechnik, Fraunhofer-Institut für Produktionsanl. und Konstruktionstech. (IPK)	Germany
YXLON International GmbH	Germany

Figure 25: Scanning of phantom on a clinical CT at DMRI.

An Inter laboratory comparison of medical CT scanners for industrial applications in the slaughterhouses was organized by DTU and DMRI using two synthetic volume phantoms simulating real pig carcasses (see WP1 for description of volume phantoms) [Rep7]. The comparison has aimed to compare volume measurement performances of different medical CT scanners in Europe. Meat is more expensive compared to fat; therefore it is important to determine the precise content of meat, fat and bones. Today the segmentation is made through a manual dissection of a large batch of carcasses, which is expensive. Using CT scanning, it would be possible to make the process automated, with reduction of time and costs. The volume phantoms circulated among four participants (Denmark, France, Germany, and Hungary) and a total of six medical CT scanners in Europe. Volume estimations were compared to reference volumes determined by water displacement (see WP1). Experiences from the participants and testing applicability of CT scanning showed a missing understanding of how to outline and implement uncertainty budgets. Future work will involve the inclusion of more institutions in a new comparison using all seven developed volume phantoms from WP1, separating the individual contributions to the differences observed. Eventually the group of institutions could open a discussion with the European Commission concerning the benefits of including a comparison scheme as a standard procedure in the European classification standardisation initiative.

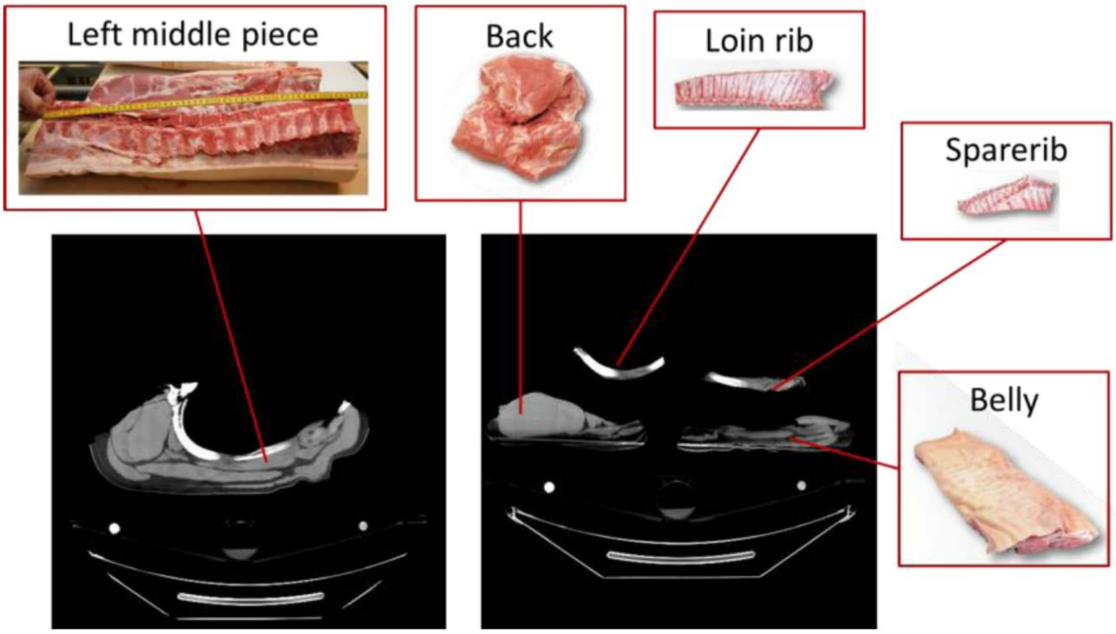

Figure 26: Scanned images of left middle piece (left) and products (right) from ImageJ software. Images of products are acquired from Danish Crown product catalogue [PhD5].

DMRI and DTU Compute have previously developed advanced image analysis software (PigClassWeb) which performs virtual dissections in pig carcasses. All scans were acquired by the mobile CT scanner “Scannerborg” at DMRI. From pig carcasses, scanned data were acquired for left products and corresponding left central piece areas, see Figure 26. A design of experiment (DOE) was carried out to document the performance of PigClassWeb through volume comparisons to real dissections of pig carcasses. For the real dissections, volumes of tissue types such as bone, lean meat and fat, are estimated using commercial VolumeGraphics software. It is detected that the analysis of variance (ANOVA) and the residuals from the virtual dissection fail the normality test. The reason can be that the simulation data has special problems and challenges which are difficult to overcome by using current regression software.

8. Initiation of new activities

The innovation consortium project has been a source for several fruitful collaborations both nationally and internationally, and a number of new initiatives were taken by consortium partners in the field of CT scanning. Among the most significant are:

- NEXIM - New X-ray Imaging Modalities for Safe and High Quality Food (Copenhagen University with 10 partners, 4M€ budget, 2012-2015, involving 4 PhD and 6 postdoc projects, funded).
- New PhD within the European Marie Curie Initial Training Network "INTERAQCT—International Network for the Training of Early stage Researchers on Advanced Quality control by Computed Tomography" (DTU, 2013-2016, funded).
- New industrial PhD on Measurements of subcutaneous insulin injections. (NBI and Novo Nordisk, 2013-2016, funded)
- New meat phantom comparison (DMRI, planned).

Further initiatives by consortium partners are expected in connection with Horizon 2020 http://ec.europa.eu/research/horizon2020 .

9. Conclusions

The innovation consortium project has aimed to help the participating companies and Danish industry with the introduction of CT scanning as measuring technology, carrying out research at international level. The project has operated through five main activities: Centre of Excellence, Dissemination, Collaboration, Research, and Initiation of new activities.

The consortium has consisted of nine partners, including three research institutions, two consultancy partners, two large companies, and two small / medium enterprises. The consortium has acted as a centre of excellence for industrial CT scanning, both nationally and internationally. A network with approx. 40 participants has been established, and a total of 22 students have been educated.

Dissemination activities have encompassed: a web page, 8 newsletters, 4 topical conferences, 5 seminars and workshops, and 61 publications.

Collaboration has been established with a number of national and international actors in the field of CT, including societies and research organisations.

Five major research projects have been carried out: 1) CT scanning for coordinate metrology; 2) Data processing for high speed scanning; 3) New beam sources and signal conditioning; 4) Equipment with high stability beam source; 5) Quality assurance and automation.

Fruitful collaborations and a number of new activities have been initiated from the project, including participation in two new project proposals and a new comparison.

The project represents a major step forward towards the industrial application of CT scanning in Denmark.

10. Publications

PhD theses

PhD1. Bech, M., **2009**, *X-ray imaging with a grating interferometer*, PhD thesis, Niels Bohr Institute.

PhD2. Jensen, T. H., **2010**, *Refraction and scattering based x-ray imaging*, PhD thesis, Niels Bohr Institute.

PhD3. Pacurar, R., **2011**, *Research on the manufacturing and dimensional control of the silicone rubber molds used in the food industry*, PhD thesis, Faculty of Machine Building, Technical University of Cluj, Romania.

PhD4. Müller, P., **2012**, *Coordinate Metrology by Traceable Computed Tomography*, PhD thesis, Technical University of Denmark.

PhD5. Angel, J., **2014**, *Quality assurance of CT scanning for industrial applications*, PhD thesis, Technical University of Denmark.

MSc theses

MSc1. Schubert, M. S., **2009**, *Detection of meat and fat quality in pork and beef using X-ray*, MSc thesis, Copenhagen University.

MSc2. Fontana, D. D., **2010**, *Metrological performance evaluation of CT scanner*, MSc thesis, Technical University of Denmark.

MSc3. Aràmbula, K., **2010**, *Coordinate metrology of a free form surface*, MSc thesis, Technical University of Denmark.

MSc4. Sauro R., **2010**, *Validation of CT scanners With Investigation on CT Data Processing*, MSc thesis, Technical University of Denmark.

MSc5. Böttiger, A., **2010**, *Differential phase contrast imaging for diagnosis of metastatic cancer in lymph nodes and initial development of reciprocal space tomography*, MSc thesis, Niels Bohr Institute.

MSc6. Sperling, L., **2010**, *Makroskopiske data på mikroskopiske målinger med røntgentomografi*, MSc thesis, Niels Bohr Institute.

MSc7. Malmstrøm Larsen, K., **2011**, *A study of the SCR DeNOx catalyst by X-ray tomography*, MSc thesis, Niels Bohr Institute.

MSc8. Thomsen, M., **2011**, *Inspection of subcutaneous injections by x-ray absorption tomography*, MSc thesis, Niels Bohr Institute.

MSc9. Pedersen, S., **2011**, *Røntgentomografi på kridt*, MSc thesis, Niels Bohr Institute.

MSc10. Nielsen, M. S., **2012**, *Novel X-ray imaging modalities - Seeing through food*, MSc thesis, Niels Bohr Institute.
MSc11. Hansen, B., **2012**, *Applications of New X-ray Imaging Modalities Looking Inside Chocolate*, MSc thesis, Niels Bohr Institute.
MSc12. Yongying Dai, **2013**, *Characterization of Components for Medical Devices by CT-Scanner and Investigation of Beam Hardening Effect on CT-Scanner Industrial Application*, MSc thesis, Technical University of Denmark.
MSc13. Ipsen, K., **2013**, *Quantitative analysis of fat and protein in meat products using X-ray tomography*, MSc thesis, Niels Bohr Institute.
MSc14. Laurberg Hansen, R., **2013**, *Quantitative analysis of fat and protein in meat products using X-ray tomography*, MSc thesis, Niels Bohr Institute.

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PJ1. Jensen, T.H., Bech, M., Zanette, I., Weitkamp, T., David, C.,Deyhle, H., Rutishauser, S., Reznikova, E., Mohr, J., Feidenhans'l, R., Pfeiffer, F., **2010**, *Directional x-ray dark-field imaging of strongly ordered systems*, Physical Review B (Condensed Matter and Materials Physics) , Vol. 82/21, pp. 214103.
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PJ3. Wadsäter, M. H., Simonsen, J. B., Lauridsen, T., Tveten, E. G., Naur, P., Bjørnholm, T., Wacklin, H., Mortensen, K., Arleth, L., Feidenhans'l, R., Cardenas Gomez, M., **2011**, *Aligning nanodiscs at the air–water interface, a neutron reflectivity study*, Langmuir , Vol. 27/24, pp. 15065-15073.
PJ4. Jensen, T. H., Bech, M., Bunk, O., Thomsen, M., Menzel, A., Bouchet, A., Le Duc, G., Feidenhans'l, R., Pfeffer, F., **2011**, *Brain tumor imaging using small-angle x-ray scattering tomography*, Physics in Medicine and Biology , Vol. 56/6, pp. 1717-1726.
PJ5. Jensen, T.H., Bech, M., Zanette, I., Weitkamp, T., David, C.,Deyhle, H., Rutishauser, S., Reznikova, E., Mohr, J., Christensen, L. B., Olsen, E. V., Feidenhans'l, R., Pfeiffer, F., **2011**, *X-ray phase-contrast tomography of porcine fat and rind*, Meat Science, Vol. 88/3, pp. 379-383.
PJ6. Jensen, T. H., Bech, M., Bunk, O., Menzel, A., Bouchet, A., Duc, G. L., Feidenhans'l, R., Pfeiffer, F., **2011**, *Molecular X-ray computed tomography of myelin in a rat brain*, NeuroImage, Vol. 57/1, pp. 124-129.
PJ7. Kruth, J.P., Carmignato, S., Schmitt, R., De Chiffre, L., Bartscher, M., Weckenmann, A., **2011**, *Computed Tomography for Dimensional Metrology*, Ann CIRP, 61/2, pp. 821-842.
PJ8. Müller, P., Hiller, J., Cantatore, A. and De Chiffre, L., **2012**, *A study on evaluation strategies in dimensional x-ray computed tomography by estimation of measurement uncertainties,* International Journal of Metrology and Quality Engineering, Vol. 3, Issue 2, pp. 107-115, doi: 10.1051/ijmqe/2012011.
PJ9. Nielsen, M. S., Lauridsen, T., Thomsen, M., Jensen, T. H., Bech, M., Christensen, L. B., Olsen, E. V., Feidenhans'l, R., Pfeiffer, F., **2012**, *X-ray tomography using the full complex index of refraction*, Physics in Medicine and Biology , Vol. 57/19, pp. 5971-5979.
PJ10. Thomsen, M., Bech, M., Velroyen, A., Herzen, J., Beckmann, F., Feidenhans'l, R.,

Pfeiffer, F., **2012**, *Visualization of subcutaneous insulin injections by x-ray computed tomography*, Physics in Medicine and Biology, Vol. 57/21, pp. 7191-7203.

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PJ12. Jensen, T. H., Bech, M., Binderup, T., Böttiger, A. P. L., David, C., Weitkamp, T., Zanette, I., Reznikova, E., Mohr, J., Rank, F., Feidenhans'l, R., Kjær, A., Højgaard, L., Pfeiffer, F., **2013**, *Imaging of metastatic lymph nodes by X-ray phase-contrast micro-tomography*, P L o S One , Vol. 8/1, pp. e54047.

PJ13. Bergbäck Knudsen, E., Prodi, A., Baltser, J., Thomsen, M., Willendrup, P. K., Sanchez del Rio, M., Ferrero, C., Feidenhans'l, R., Mortensen, K., Nielsen, M. M., Poulsen, H. F., Farhi, E., Schmidt, S., Lefmann, K., McXtrace, **2013**, *A general software package for simulation of X-ray optics, beamlines, and experiments*, Journal of Applied Crystallography , Vol. 46/3, pp. 679-696.

PJ14. Angel, J., De Chiffre, L., **2014**, *Comparison on Computed Tomography using industrial items*, CIRP Annals, Vol. 63/1, In press.

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PJ16. Lauridsen, T., Lauridsen, E.M., Feidenhans'l, R., **2014** *Mapping misoriented fibers using X-ray dark field tomography*, Applied Physics A, Accepted.

PJ17. Gameros, A., De Chiffre, L., Siller, H., Figueroa, O., Hiller, J., *Reverse engineering methodology for nickel alloy turbine blades with internal features*, CIRP Journal of Manufacturing Science and Technology, (submitted).

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PC1. Christensen L. B., Erbou, S. G., Vester-Christensen, M., Hansen, M. F., Darré, M., Hviid, M. and Olsen, E. V., **2010**, *Optimized workflow and validation of carcass CT-scanning*, 56th International Congress of Meat Science and Technology, Jeju Island, South Korea.

PC2. Cantatore, A., Andreasen, J.L., Carmignato, S., Müller, P. and De Chiffre, L., **2011**, *Verification of a CT scanner using a miniature step gauge*, Proceedings of the 11th euspen International Conference, Como, Italy, pp.46-49, ISBN13: 978-0-9553082-9-1.

PC3. Müller, P., Hiller, J., Cantatore, A. and De Chiffre, L., **2011**, *Investigation of measuring strategies in computed tomography*, Proceedings of the International conference on Advanced Manufacturing Engineering (NEWTECH 2011), Brno, Czech Republic, pp. 31-42, ISBN 978-80-214-4267-2.

PC4. Müller, P., Pacurar, R.A., De Chiffre, L., Cantatore, A. and Berce, P., **2011**, *Geometrical metrology on silicone rubber by computed tomography*, Proceedings of the 11th euspen International Conference, Como, Italy, pp.243-246, ISBN13: 978-0-9553082-9-1.

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the 12th euspen International Conference, Stockholm, Sweden, pp. 72-75.
PC7. Müller, P., Cantatore, A., Andreasen J. L., Hiller, J., De Chiffre, L., **2012**, *Computed Tomography as a Tool for Tolerance Verification of Industrial Part*, CIRP Conference on Computer Aided Tolerancing, Huddersfield, UK.

PC8. Angel, J., Cantatore, A., De Chiffre, L., **2012**, *Preliminary results of a proficiency testing of industrial CT scanners using small polymer items*, Proceedings of the 12th euspen International Conference, Stockholm, Sweden, pp. 162-165.

PC9. Cantatore, A., Angel, J., De Chiffre, L., **2012**, *Material investigation for manufacturing of reference step gauges for CT scanning verification*, Proceedings of the 12th euspen International Conference, Stockholm, Sweden, pp. 129-132.

PC10. Tan, Y., Kiekens, K., Welkenhuyzen, F., Angel, J., De Chiffre, L., Kruth, J. P., Dewulf, W., **2013**, *Simulation-aided investigation of beam hardening induced errors in CT dimensional metrology*, The 11th International Symposium of Measurement Technology and Intelligent Instruments, Aachen, Germany, pp. 1-7.

PC11. Santo, L., Quadrini, F., De Chiffre, L., **2013**, *Forming of shape memory composite structures*, Key Engineering Materials (ISSN: 1013-9826) (http://dx.doi.org/10.4028/www.scientific.net/KEM.554-557.1930), vol: 554-557, pp. 1930-1937.

PC12. Müller, P., Cantatore, A., Andreasen, J. L., Hiller, J., De Chiffre, L., **2013**, *Computed tomography as a tool for tolerance verification of industrial parts*, 12th CIRP Conference on Computer Aided Tolerancing, Huddersfield, Procedia CIRP (ISSN: 22128271) (http://dx.doi.org/10.1016/j.procir.2013.08.022), vol: 10, pp.125-132.

PC13. Christensen, L. B., Angel, J., **2013**, *Inter-laboratory comparison of medical computed tomography (CT) scanners for industrial applications in the slaughterhouses*, Farm Animal IMaging FAIM II, Kaposvár, Hungary, pp. 27-32, ISBN 978-0-9570709-9-8.

PC14. Angel, J., Lauridsen, T., Feidenhans'l, R., Nielsen, M. S., De Chiffre, L., **2014**, *Using grating based X-ray contrast modalities for metrology*, Proceedings of the euspen International Conference. Dubrovnik, Croatia, In press.

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Rep1. Müller, P., **2010**, *Use of reference objects for correction of measuring errors in X-ray computed tomography*, Department of Mechanical Engineering, Technical University of Denmark.

Rep2. Pacurar, R, Müller, P, De Chiffre, L., **2011**, *Geometrical metrology on vacuum cast silicone rubber form using computed tomography*, Department of Mechanical Engineering, Technical University of Denmark.

Rep3. Cantatore, A., Müller, P., **2011**, *Introduction to computed tomography*, Department of Mechanical Engineering, Technical University of Denmark.

Rep4. Angel, J., De Chiffre, L., Larsen, E., Rasmussen, J., **2012**, *CIA-CT comparison – Inter laboratory comparison on Industrial Computed Tomography*, Technical Protocol, Department of Mechanical Engineering, Technical University of Denmark.

Rep5. Angel, J., De Chiffre, L., Larsen, E., Rasmussen, J., Sobiecki, R., **2013**, *CIA-CT comparison – Inter laboratory comparison on Industrial Computed Tomography*, Reference Measurements, Department of Mechanical Engineering, Technical University of Denmark.

Rep6. Angel, J., De Chiffre, L., **2013**, *CIA-CT comparison – Inter laboratory comparison on Industrial Computed Tomography*, Final Report, Department of Mechanical

Engineering, Technical University of Denmark.

Rep7. Angel, J., Christensen, L. B., De Chiffre, L., Cantatore, A., **2014**, *CIA-CT comparison – Inter laboratory comparison on Computed Tomography for industrial applications in the slaughterhouses*, Department of Mechanical Engineering, Technical University of Denmark.

Presentations at conferences and seminars

Pres1. Müller, P., *CIA-CT WP1 Road Map CIA-CT Seminar on ""CIA-CT WP1 Road Map"*, DTU, Kgs. Lyngby, Denmark, **July 8, 2010**.

Pres2. Müller, P., *Geometrical metrology on silicone rubber by computed tomography*, euspen 2011, Como, Italy, **May 26-28, 2011**.

Pres3. Müller, P*., Influence parameters in CT scanning, 2nd CIA-CT Conference on "Application of CT scanning in industry"*, Teknologisk Institut (DTI), Høje Taastrup, Denmark, **May 31, 2011**.

Pres4. Angel, J., *CT Metrology – CT Round Robin, 2nd CIA-CT Conference on "Application of CT scanning in industry"*, DTI, Høje Taastrup, Denmark, **May 31, 2011**.

Pres5. Müller, P., *Investigation of measuring strategies in computed tomography*, NEWTECH 2011 (International conference on advanced manufacturing engineering), Brno, Czech Republic, **September 14-15, 2011**.

Pres6. Müller, P., *Computed Tomography as a Tool for Tolerance Verification of Industrial Part*, 12th CIRP conference on Computer Aided Tolerancing, Huddersfield, UK, **April 18-19, 2012**.

Pres7. Müller, P., *New reference object for metrological performance testing of industrial CT systems*, euspen 2012, Stockholm, Sweden, **June 4-8, 2012**.

Pres8. Angel, J., *Preliminary results of a proficiency testing of industrial CT scanners using small polymer items*, euspen 12th International conference, Stockholm, Sweden, **June 4-7, 2012**.

Pres9. Angel, J., *Material investigation for manufacturing of reference step gauges for CT scanning verification*, euspen 12th International conference, Stockholm, Sweden, **June 4-7, 2012**.

Pres10. Larsen, E., *A new intercomparison for industrial CT scanners, 3rd CIA-CT Conference on "Industrial Applications of CT Scanning – Possibilities & Challenges in the Manufacturing Industry"*, DTU, Kgs. Lyngby, Denmark, **June 12, 2012**.

Pres11. Angel, J., *CT Workshop, CIA-CT Comparison Workshop*, DTU, Kgs. Lyngby, Denmark, **September 5, 2012**.

Pres12. Müller, P., *Investigation on the influence of image quality in X-ray CT metrology*, Conference on Industrial Computed Tomography (ICT), Wels, Austria, **September 19-20, 2012**.

Pres13. Larsen, E., *CIA-CT comparison - Interlaboratory comparison of industrial CT scanners*, Presentation of Technical Protocol, CIA-CT Comparison Workshop, DTU, Kgs. Lyngby, Denmark, **November 27, 2012**.

Pres14. Angel, J., *Inter laboratory comparison of medical CT scanners for industrial applications in the slaughterhouses CIA-CT Comparison Workshop*, DTU, Kgs. Lyngby, Denmark, **January 15, 2013**.

Pres15. Angel, J., *CIA-CT Comparison Final Report, CIA-CT Comparison Workshop*, DTU, Kgs. Lyngby, Denmark, **June 20, 2013**.

Pres16. Angel, J., De Chiffre, L., *CIA-CT comparison Inter laboratory comparison on Industrial Computed Tomography*, Poster session presented at 5th International Conference on Industrial Computed Tomography (iCT), Wels, Austria, **February 25-28, 2014**.

Newsletters

New1. *CIA-CT Project newsletter nr 1*, **November 2009**, Department of Mechanical Engineering, Technical University of Denmark. Kgs. Lyngby, Denmark.
New2. *CIA-CT Project newsletter nr 2*, **May 2010**, Department of Mechanical Engineering, Technical University of Denmark. Kgs. Lyngby, Denmark.
New3. *CIA-CT Project newsletter nr 3*, **November 2010**, Department of Mechanical Engineering, Technical University of Denmark. Kgs. Lyngby, Denmark.
New4. *CIA-CT Project newsletter nr 4*, **May 2011**, Department of Mechanical Engineering, Technical University of Denmark. Kgs. Lyngby, Denmark.
New5. *CIA-CT Project newsletter nr 5*, **November 2011**, Department of Mechanical Engineering, Technical University of Denmark. Kgs. Lyngby, Denmark.
New6. *CIA-CT Project newsletter nr 6*, **May 2012**, Department of Mechanical Engineering, Technical University of Denmark. Kgs. Lyngby, Denmark.
New7. *CIA-CT Project newsletter nr 7*, **December 2012**, Department of Mechanical Engineering, Technical University of Denmark. Kgs. Lyngby, Denmark.
New8. *CIA-CT Project newsletter nr 8*, **June 2013**, Department of Mechanical Engineering, Technical University of Denmark. Kgs. Lyngby, Denmark.

Web site

- www.cia-ct.mek.dtu.dk

Conferences

Con1. *1st CIA-CT Conference on "Application of CT scanning in industry"*, DTU, Kgs. Lyngby, Denmark, **June 8, 2010** (Editor: De Chiffre, L.).
Con2. *2nd CIA-CT Conference on "Application of CT scanning in industry"*, DTI, Høje Taastrup, Denmark, **May 31, 2011** (Editors: Holmberg, M., De Chiffre, L.).
Con3. *3rd CIA-CT Conference on "Industrial Applications of CT Scanning – Possibilities & Challenges in the Manufacturing Industry"*, IPU, Kgs. Lyngby, Denmark, **June 12, 2012** (Editors: Larsen, E., De Chiffre, L.).
Con4. *4th CIA-CT Conference on "Applications of Computed Tomography in Industrial Production"*, NBI, Copenhagen, Denmark, **June 19, 2013** (Editors: De Chiffre, L., Feidenhans'l, R. K.).

Seminars/Workshops

S/W1. *CIA-CT Seminar*, DTU, Kgs. Lyngby, Denmark, **July 8, 2010**.
S/W2. *CIA-CT Industrial Comparison Planning Workshop*, DTU, Kgs. Lyngby, Denmark, **September 5, 2012**.
S/W3. *CIA-CT Industrial Comparison Planning Workshop*, DTU, Kgs. Lyngby, Denmark, **November 27, 2012**.
S/W4. *CIA-CT Slaughterhouse Comparison Final Workshop*, DTU, Kgs. Lyngby, Denmark, **January 15, 2013**.

S/W5. *CIA-CT Industrial Comparison Final Workshop*, DTU, Kgs. Lyngby, Denmark, **June 20, 2013**.