

# Dimensional X-ray Computed Tomography Conference 2018

Tuesday 3<sup>rd</sup> July 2018 University of Nottingham





Programme

# Dear delegates,

The organising committee takes great pleasure in welcoming you to the second NPL Dimensional X-ray Computed Tomography (dXCT) conference, this year held at the Jubilee conference centre, University of Nottingham.

This one day conference will address developments in dimensional XCT from acquisition and processing methodologies, through to improving manufacturing methods and applications. The programme has been developed with the community to share knowledge within the field, explore developing requirements of industry and gain insight from others.

Oral presentations by invited speakers and selected poster presentations will be given by scientists and students to demonstrate the latest research. The day finishes with a panel discussion to deliberate requirements in the field and identify future industry needs. Throughout the conference, there are also a number of opportunities to network with academics, industry leaders, scientists and researchers.

We are grateful to all of our sponsors who have helped make this event possible. Sponsor's exhibits are available during the breaks to discuss their recent software and hardware developments. In addition, we would like to thank both NPL and the University of Nottingham for providing workshops the day before the conference that will have been of significant benefit to the community. Finally we would like to acknowledge the support of Diane Karim of the University of Nottingham in the conference organisation.

We hope the conference serves as a platform for fruitful communication between scientific and industrial communities. We look forward to an interesting and stimulating conference, and wish you a warm welcome to the University of Nottingham.

Kind Regards,

**Organising Committee** 

# Venue information



**Parking** Please print, complete and display the parking voucher sent to you via email. Parking is available outside the conference centre (please see the "useful information for delegates" document for exact location information).

**Wi-fi** The venue has free wi-fi access for conference delegates, and "eduroam" is available if you are setup on that network. Please see the guide at the end of this document for joining instructions.

**Exhibitors** can be found in the break-out area throughout the conference.

**Coffee/lunch** Coffee will be provided at intervals throughout the conference in the foyer area outside the main theatre. Lunch will also be served here.

# Programme

| 08:30 | Registration/Coffee   |
|-------|---|
|       | <b>Session 1</b><br>Session Chair – Richard Leach   |
|       |   |
| 9:30  | Opening comments<br>Richard Leach; University of Nottingham   |
| 9:40  | Keynote 1: Performance verification of industrial CT systems – how do you know a system meets specification?<br>Michael McCarthy; Engineering Metrology Solutions |
| 10:10 | Toward Dimension X-ray Computed Tomography for Smart Manufacturing<br>Liming Li; National Physical Laboratory/JSL Innovations Inc                                 |
| 10.30 | Digital Inspection of multi-material industrial parts<br>Andreas Staude; Thermo Fisher Scientific   |
| 10.50 | Coffee  |

# Session 2

# Session Chair – Adam Thompson

| 11.20 | Effects of sinogram interpolation for increasing throughput rate of surface topography measurements using X-ray computed tomography <i>Lars Körner; University of Nottingham</i>   |
|-------|--|
| 11.40 | Hyper-parameter selection for accurate reconstruction in XCT tomography<br>Stephane Chretien; National Physical Laboratory/University of Bath  |
| 12.00 | Effect of Thickness Variation on Dimensional Measurement and Surface<br>Morphology of Additively Manufactured Thin Walled Structures Investigated<br>by X-ray Computed Tomography<br><i>Amir Reza Zekavat; Örebro University</i> |
| 12.20 |  |
| 12.20 | Lunch  |

# Session 3

Session Chair – Stephen Brown

| 13.20 | Keynote 2: Use of μ-XCT in the medical devices industry<br>Paul A. Gunning; Smith & Nephew  |
|-------|---|
| 13.50 | X-ray computed tomography investigation of additive manufactured acetabular hip prosthesis <i>Nadia Kourra; University of Warwick</i> |
| 14.10 | XCT Dimensional Measurement Workflow Influences<br>Nathanael Turner; Manufacturing Technology Centre                                  |
|       |   |

| 14.30 | Coffee and poster session |  |
|-------|---------------------------|--|
|-------|---------------------------|--|

#### Session 4

#### Session Chair – Wenjuan Sun

| 15.10 | Optimisation of compact laser-driven accelerator x-ray sources for imaging applications<br>Daniel Symes; STFC Rutherford Appleton Laboratory               |
|-------|--|
| 15.30 | Development of 2D Local Adaptive Algorithms for Surface Determination of X-<br>ray Computed Tomography Measurement<br>Shan Lou; University of Huddersfield |
| 15.50 | The optimisation of X-ray CT data collection and automated analysis for industrial applications <i>Tristan Lowe; University of Manchester</i>              |
| 16:10 | Panel Discussion<br>Wenjuan Sun (chair); National Physical Laboratory  |
| 16:40 | Intro to dXCT 2019 and 2020<br>Paul Bills and Martin Turner; University of Huddersfield and University of<br>Manchester                                    |
| 16:50 | Closing remarks and prize giving<br>Wenjuan Sun (chair); National Physical Laboratory  |

17:00 Close

# Sponsors and Exhibitors





# Organising Committee

#### **Conference Chairs**

Dr Wenjuan SunNational Physical LaboratoryProf Richard LeachUniversity of Nottingham

**Conference Co-chairs** 

Mr Adam Thompson Mr Stephen Brown University of Nottingham National Physical Laboratory

#### **Committee Members**

Prof Michael McCarthy Dr Alex Attridge Dr Farah Ahmed Dr Paul Bills Prof Ian Sinclair Mr Lars Körner Dr Xiaobing Feng Dr Martin Turner Prof Mark Williams Engineering Metrology Solutions WMG, University of Warwick Exponent University of Huddersfield University of Southampton University of Nottingham University of Nottingham University of Manchester WMG, University of Warwick

Oral presentations

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# Performance verification of industrial CT systems – how do you know a system meets specification?

Michael McCarthy

**Engineering Metrology Solutions** 

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#### Abstract

This presentation will be invaluable to anybody wanting to confidently perform dimensional measurements using an XCT system and requiring length data traceable to national standards, such as supported by NPL or other leading NMIs.

Setting a scene...Consider a company already using an XCT system with dimensional capabilities; or alternatively, you are interested in using or even investing in an XCT system.

How can you be confident that any of those length type numbers (micrometres?) on a manufacturer's performance specifications sheet can actually be delivered by the instrument? Perhaps the instrument does not have a detailed performance specification sheet? Then what questions and practical tests should an end user request a supplier to perform?

Just how can one be confident in the performance of an individual system's performance over its entire operating range? Furthermore, how does one compare the performance of different systems, particularly when each manufacturer seems to quote specifications in slightly different ways?

This presentation will provide an overview of the most up-to-date developments with a proposed dimensional XCT standard, namely ISO 10360 part 11. Once published, it is anticipated that most manufactures will need to revisit their specifications; but how attractive will the numbers be, once an agreed common verification process is available?

#### 2<sup>nd</sup> – 3<sup>rd</sup> July 2018 University of Nottingham



# Toward Dimension X-ray Computed Tomography for Smart Manufacturing

Liming Li<sup>1,2</sup>, Wenjuan Sun<sup>1</sup> and Stephen Brown<sup>1</sup>

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#### Abstract

Smart manufacturing is one important aspect of industry 4.0. Many manufacturing enterprises are investing more to deploy smart manufacturing in the manufacturing process through the modelbased enterprise (MBE), big data and internet of things (IoT) technologies. With minimum human involvement in the process, smart manufacturing optimises the entire product process, greatly enhancing the throughput, product quality and increasing profit margin. Smart manufacturing is applicable to product lifecycle management, covering each stage of manufacturing process from: design, manufacturing, inspection to the final product.

The inspection stage (including measurement and quality control) in the manufacturing process is fundamental to smart manufacturing. Driven by the need of quality control of complex engineering parts and enabled by developments in imaging technologies, computing power and graphics processing unit, X-ray computed tomography (XCT) has been increasingly used for industrial inspection in the last decade. The benefits of using XCT for inspection and quality control is driving manufacturers to consider the possibilities of deploying XCT capability to their production lines. However, the complexity of set-up procedures, speed of data capture, handling and visualisation are challenges that have limited the application of this technology. This presentation introduces the approach to implement the XCT inspection for smart manufacturing.

In smart manufacturing, the design model and product manufacturing information (PMI) of the inspection objects are known. By the use of the XCT inspection principle and predefined object characteristics such as geometry and material, inspection solutions can be developed. These solutions can optimise the setup procedure, speed up data handling, automatically evaluate geometric dimensioning and tolerancing (GD&T) and generate technical product documentation (TPD). The approach includes two parts, pre-process and post-process.

The use of a pre-process, using a virtual XCT system that simulates all XCT-processes, will allow optimisation of parameters for greater accuracy and optimisation of measurement time by utilising the model-based design (MBD) data as input information.

For the post-process, the development of new algorithms in surface determination, filtering by taking advantage of given design models and PMI to reduce the size of data while improving data quality, automatically speed up evaluating GD&T and generate standard TPD that is compliant with international standards.

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### Digital Inspection of multi-material industrial parts.

Patrick Barthelemy<sup>1</sup>, Peter Westenberger<sup>1</sup>

<sup>1</sup> Thermo Fisher Scientific

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#### Abstract

Dimensional metrology on digital CT model of mono-material industrial parts is based on determination of the interface between air and the part. Precise determination of this surface can be difficult due to acquisition artefact that can include noise, partial volume effect, streaks, or beam hardening for instance. Different methods allows for adjustment of the interface based on an initial iso-surface that can use different thresholds such as local minima, ISO50 or Otsu. In the case of multi-materials part, the problem is even more complex as the intensity range of the CT for each component can overlap and a single threshold can belong to multiple materials. This talk will demonstrate different approaches and result of segmentation on multi-material CT data and how precise interface between each material can be extracted.

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# Effects of sinogram interpolation for increasing throughput rate of surface topography measurements using X-ray computed tomography

Lars Körner<sup>1</sup>, Simon Lawes<sup>1</sup>, Lewis Newton<sup>1</sup>, Nicola Senin<sup>1,2</sup>, Richard Leach<sup>1</sup>

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#### Abstract

X-ray computed tomography (XCT) is a non-destructive imaging technique, in which a large set of radiographs is used to solve an inverse problem. This inverse problem is the reconstruction of the attenuation behaviour within the scanned volume. Modern XCT systems can easily require the acquisition of 3000+ radiographs to reconstruct the volume. While other approaches to reduce this number include iterative reconstruction algorithms, the work presented here utilises an approach discussed in the early medical literature: the interpolation of the sinogram data. In this work, an additively manufactured part is used as a test specimen to explore the effects of different degrees of sinogram interpolation. Datasets are collected with the full number of radiographs needed (3142 projections for this XCT system and setup) as well as with a reduced number of radiographs: 20%, 40%, 60% and 80% of the 3142 projections. The collected sinograms are then interpolated to create upsampled data sets and are reconstructed. The reconstructed volumes are analysed in terms of noise and resolution. To evaluate noise, the Shannon entropy is used as a comparison value. To evaluate resolution, an oversampled edge spread function approach is used. Surface topography data obtained from the reconstructed volumes are compared numerically and by computing areal surface texture parameters. The results reveal that the experimental condition with the least noise is, as expected, the one with the full set of radiographs. However up-sampling the sinogram data reduces the noise for all the under-sampled test conditions. The resolution is worst when using only 628 radiographs (20%). The oversampled edge spread function approach is not repeatable enough to quantify the differences between the remaining test conditions. The topography comparison showed evidence that using only 1257 (40%) radiographs but interpolating the 1257 radiographs to 3142 projections creates similar results to those obtained using 2514 (80%), or even 3142 radiographs for the presented test case.

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# Hyper-parameter selection for accurate reconstruction in XCT tomography

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#### Abstract

Image reconstruction in X-ray computed tomography (XCT) is an ill posed problem which is usually addressed using regularisation techniques. A given set of projections is acquired from an XCT scan and the fidelity of a 3D candidate image, A, for reconstruction with respect to the projections is defined as the squared error between the observed projections and their values if the image is set to be equal to A. Due to the ill posed nature of the problem, many different images may have a small fidelity with respect to the observed projections. As a result, minimising the fidelity cannot in general solve the reconstruction problem. The regularisation approach consists in minimising the fidelity plus consideration of an additional penalisation term, which is designed so as to enforce the essential features common to the class of admissible images. Oftentimes, the penalisation term consists of several functions and weights which usually enable the practitioner to impose an appropriate balance between the many features to be enforced. Accurate choice of the weights, also called hyperparameters in the statistical Bayesian literature, is a delicate problem in XCT reconstruction, especially when the number of hyper-parameters is large. We propose a new technique for hyper-parameter selection based on online learning [1]. More precisely, we design a procedure which combines (a) the Hedge algorithm of Freund and Shapire [2] with (b) sequential reconstruction steps based on successive incorporation of new projections. A probability distribution on the set of potential hyperparameters is updated with every new projection and the hyper-parameter with highest probability is selected for the reconstruction. The entropy of the distribution at convergence is a good index of the quality of the projection sequence, which can be used in order to decide if more projections are necessary or if sufficient information has already been collected. We compare the new approach with various algorithms previously proposed in the literature. The preliminary study shows that our method often outperforms the other strategies using simulation data.

- Hazan E. Introduction to online convex optimization. Foundations and Trends in Optimization, vol. 2, no. 3-4, 157-325, 2015, now Publishers Inc.
- 2. Freund Y, and Schapire RE. A decision-theoretic generalization of on-line learning and an application to boosting. Journal of Computer and System Sciences 55, 119-139, 1997.

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# Effect of Thickness Variation on Dimensional Measurement and Surface Morphology of Additively Manufactured Thin Walled Structures Investigated by X-ray Computed Tomography

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#### Abstract

Additive manufacturing (AM) technologies have been experiencing a rapid development in the last decade. Their ability to produce near net shape parts as well as parts with geometrical complexity has resulted in an ever increasing application of AM parts in different branches of science and industry such as aerospace, automotive and biomedicine. Despite the considerable advantages of AM technologies there are challenges which need to be investigated. One of the limiting factors in AM process especially in case of powder bed metal processes is the surface quality of as-built parts. The increasing demand for high quality AM parts requires thorough investigations of AM surfaces. Due to complexity of AM surfaces, conventional methods such as tactile and optical surface measurement methods are incapable of thorough inspection of such surfaces. However, X-ray computed tomography (CT) has shown its capabilities for capturing three dimensional detailed information of AM surfaces including re-entrant features and valleys which cannot be captured using conventional surface measurement methods. The aim of this study is to investigate the effect of designed thickness of additively manufactured thin walled structures on their dimensional measurement which is influenced by surface morphology. Five AlSi10Mg flat thin walled structure with thicknesses ranging from 400 to 2000 µm were fabricated using selective laser melting method. The specimens were scanned using an XRADIA XRM 410 CT system resulting in voxel size of 4.8 µm. A selected region of interest at specific build height from each specimen was used for detailed analysis of surface features such as partially molten powder particles and re-entrants contributing to different minimum and maximum thickness measurement results. It was concluded that the resulting as-built minimum and maximum thicknesses of thin walled structures were influenced by their designed thicknesses. The main contributors to this phenomena was the attachment of partially molten powder particles as well as deep valleys. This phenomena which contributes to bigger dimensional deviation from as-designed geometry especially for thinner specimens should be considered at design stage.

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### Use of $\mu$ -XCT in the medical device industry

Paul A. Gunning

Smith & Nephew

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#### Abstract

Globally, healthcare systems are facing increased demand from ageing populations due to increasing societal pressure to maintain active lifestyles and fitness for work past the age of 60 years. The Medical Device industry has a critical role to play in addressing these issues by innovating to find ever more cost-effective products. Measurement is critical to demonstrating safety and efficacy of new and existing medical devices and to securing intellectual property within this stringently regulated industry. Image analysis offers powerful methodologies for extracting 'measurements' from 2 and 3 dimensional images, but many analyses involve a degree of subjectivity when selecting image features based on a greyscale or colour threshold/segmentation. This presentation will provide examples of measurement challenges with respect to both Wound Care and Orthopaedic medical devices, covering both manufacturing qualification and new product development:

Determination of gas cell size distribution in polyurethane foams was historically achieved using scanning electron microscopy of 2-dimensional surfaces across multiple cross-sections, but the methodology suffered from potential stereographic errors (inferring 3-dimensional data from 2-dimesnional cross-sections). Use of  $\mu$ -XCT for this analysis provides less potential for stereographic error, whilst also enabling larger statistical datasets to be obtained with minimal physical perturbation to the foams.

Bioresorbable implants offer a bone-conserving surgical method for the deployment of connective tissue repair products such as tendon-repair suture anchor systems. Explanted tissue  $\mu$ -XCT provides a rapid and relatively non-destructive method to determine the extent of resorption and new bone growth for pre-clinical evaluation of such products and the non-destructive nature of  $\mu$ -XCT is helpful in pinpointing regions of interest within explants for lengthier classical histology/pathology specimen preparation.

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# X-ray computed tomography investigation of additive manufactured acetabular hip prosthesis

Nadia Kourra<sup>1</sup>, Jason M. Warnett<sup>1</sup>, Alex Attridge<sup>1</sup>, Greg Dibling<sup>2</sup>, James McLoughlin<sup>2</sup>, Sarah Muirhead-Allwood<sup>3</sup>, Richard King<sup>4</sup>, Mark A. Williams<sup>1</sup>

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#### Abstract

Additive Manufacturing (AM) is uniquely suitable for healthcare applications due to its design flexibility and cost effectiveness for creating complex geometries. Successful arthroplasty requires integration of the prosthetic implant with the bone to replace the damaged joint. Bone-mimetic biomaterials are utilised due to their mechanical properties and porous structure that allows bone ingrowth and implant fixation. The predictability of predetermined interconnected porous structures produced by AM ensures the required shape, size and properties that are suitable for tissue ingrowth and prevention of the implant loosening. The quality of the manufacturing process needs to be established before the utilisation of the parts in healthcare. This paper demonstrates a novel examination method of acetabular hip prosthesis cups based on X-ray Computed Tomography (CT) and image processing. The method was developed based on an innovative hip prosthesis acetabular cup prototype with a prescribed non-uniform lattice structure forming struts over the surface, with the interconnected porosity encouraging bone adhesion. This non-destructive, non-contact examination method can provide information of the interconnectivity of the porous structure, the standard deviation of the size of the pores and struts, the local thickness of the lattice structure in its size and spatial distribution. In particular, this leads to easier identification of weak regions that could inhibit a successful bond with the bone.



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#### **XCT Dimensional Measurement Workflow Influences**

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#### Abstract

A large number of influence factors associated with the analysis workflow after the data acquisition contribute to the measurement output in dimensional X-ray Computed Tomography (XCT). Specifically, surface determination, meshing and the fitting of measurands can be performed in a number of different software packages, offering different algorithms (some proprietary) and implementations, often featuring user-adjustable parameters, with implications for the final measurements obtained. This work assesses the impact of changes to the workflow for experimental data, obtained from two industrially-relevant test pieces with a selection of associated measurands, using a range of software packages and configurations. Outputs from different commercially available implementations of the same thresholding method are compared, alongside the outputs of proprietary locally adaptive surface determination methods. The impact of different meshing implementations and options is similarly explored. The work highlights the contribution of the data analysis workflow to the measurement system uncertainty.

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# Optimisation of compact laser-driven accelerator x-ray sources for imaging applications

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#### Abstract

Commercial machines employed for industrial imaging often rely on electron impact x-ray tube technology that suffer from certain limitations on image resolution and scan speed. Advanced imaging capability can be achieved using synchrotron light sources but these are national-scale facilities and not suitable for in situ inspection. We present an alternative compact light source based on a high power laser (> 100 TW) that delivers extreme brightness ultrashort x-ray pulses ideally suited for deployment in industrial environments. The laser is used to drive a cm-scale plasma accelerator generating femtosecond relativistic electron bunches with GeV energy that can be converted to x-ray beams through a plasma betatron process or bremsstrahlung radiation. This produces up to  $10^{10}$  photons per pulse in the x-ray region spanning 10 keV up to multi-MeV. The beam is spatially coherent because of the micron-scale source size, enabling phase enhanced imaging to improve contrast between low *Z* materials with similar density.

Using the Gemini laser at RAL we have demonstrated the feasibility of using laser-based radiation for high resolution non-destructive evaluation of industrial components. The same laser can generate x-ray energies in the 10's keV range for low density polymer and composite materials and in the multi-MeV range for penetration of large dense samples such as automotive or aerospace components. We will describe an experimental campaign characterising the properties of the x-ray beams and present example images of a range of samples provided by industrial partners. These covered three particular areas of importance to UK industry: quality control of composites, metrology of additive manufactured test samples and characterisation of battery electrodes. We will discuss the potential of these sources for high frame rate industrial XCT as the drive lasers move towards operation at the 10 - 100 Hz repetition rate in the next few years.

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# Development of 2D Local Adaptive Algorithms for Surface Determination of X-ray Computed Tomography Measurement

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#### Abstract

Surface determination is one of the major error sources of X-ray computed tomography (XCT) measurements. The ISO 50 method is found not be able to determine an accurate surface boundary. Commercial XCT data analysis software provides advanced algorithms for precise surface determination, e.g. the local adaptive edge detection algorithm, but they remain in a black box and relevant information is very limited. Local searching algorithms are implemented to generate the surface contours from 2D cross-section images of a 3D object. The local adaptive algorithm takes the ISO 50 contour as the initial boundary, based on which it searches for the maximum gradient along contour normals. The local iterative algorithm automatically expands its searching distance until the local maximum gradient converges. The two algorithms can be optimised in different aspects. A spline filter can be applied to smooth the initial contour and thus generate more stable contour normals. Bicubic interpolation can be used to locate the maximum gradient position more accurately (at subpixel level). The searching distance, the increment distance and the maximum iteration number can also be customised. In this study, simulated XCT data is used for testing purposes. A CAD model of a cylinder is designed, comprising an ideal cylinder and sinusoidal waves superimposed on the cylinder surface to simulate surface texture. The CAD model is meshed and imported into aRTist (a XCT simulation software). The cross-section slice images extracted from the reconstructed cylinder volume data are analysed by the ISO 50 method and the developed local searching algorithms. The comparison shows the local searching algorithms are more accurate for dimensional and surface measurement.



**Figure 1.** Cylinder circumference contours generated by the ISO 50 method and the developed local adaptive algorithm.

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# The optimisation of X-ray CT data collection and automated analysis for industrial applications

Lowe T<sup>1</sup>, Westenberger P<sup>2</sup>, Johnson S, Warr R<sup>1</sup>, Ramsey A<sup>3</sup>, Dickinson M<sup>1</sup> & Withers P. J.<sup>1</sup>

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<sup>3</sup> NIKON METROLOGY

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#### Abstract

Micro X-ray Computed Tomography (CT) has become an established Non-Destructive Testing (NDT) technique in both academic research and industrial applications. Despite the rapid development of X-ray CT in the last two decades the technique is still in its infancy with no defined world standard on data collection and interpretation, which has led to variability in analysis. This talk explores how simple X-ray spot measurements can be used to calculate the optimum imaging positions for both small and highly dense specimens. The use of radiographic spatial targets combined with numerical characterisation are then used to define raw data quality and estimate errors in post processing. This informed knowledge regarding X-ray CT raw data is essential in the implication of automated NDT in the commercial sector and the allocation of defect errors and surface tolerance measurements.

Poster presentations

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# Internal surface measurement by X-ray computed tomography: an additive manufacturing industrial case study

Adam Thompson<sup>1</sup>, Ian Maskery<sup>2</sup>, Richard Leach<sup>1</sup>

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#### Abstract

Additive manufacturing (AM) processes have been lauded for their ability to produce highly complex geometries that are otherwise not manufacturable. This includes lattice structures and internal cooling channels. Such structures may have a revolutionary impact on the aerospace, automotive and medical sectors because of their associated functional properties; for example, significant savings in weight, impact energy absorption, vibration isolation and thermal management. However, such structures present issues in verification, as crucial surface features are often difficult-to-access or entirely separated from the outside, and so cannot be measured by established optical or contact methods. Recent work has demonstrated the feasibility of X-ray computed tomography (XCT) for the measurement of internal and hard-to-access surfaces. Using designed-for-purpose separable assemblies, pseudo-internal surfaces have been investigated by comparison of XCT data to that acquired using established measurement technologies. Here, we present a case study of an XCT surface measurement, using an industrially representative sample comprising a metal AM Ti6Al4V cube of  $(20 \times 20 \times 20)$  mm containing internal channels. The cube will be measured by XCT at two different magnification settings and assessments of internal surfaces made based on the resulting data (see figure 1). The cube will then be sectioned in order to perform measurements by conventional techniques and comparisons of direct topographies as well as generated ISO 25178-2 parameters will be made between datasets.



Figure 1. Top and bottom of measured channel, extracted from XCT data.

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# Optimization of surface determination to improve the detection of unfused powder in SLM Aluminium 3D printed component.

Ahmed Tawfik, Paul Bills, Liam Blunt, Radu Racasan. EPSRC Future Advanced Metrology Hub

University of Huddersfield

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#### Abstract

Additive manufacturing (AM) is quickly being recognized as a core technology for producing complex and individual components, so the need for well understood non-destructive testing is more urgent than ever. The mechanical properties of cast components are well studied and non-destructive testing is well established by various methods like XCT and ultrasound. On the other hand, there are big challenges for additive manufactured components due to the difference in pores/defects found in AM components. The pores found in additive manufactured components are different from those found in cast alternatives. In the additive manufactured components, the pores could be hollow, filled with partially fused powder or unfused powder. The pores found in cast components are usually hollow.

This paper investigates the impact of surface determination on the detection of unfused powder in a SLM process and assesses the ability of utilizing the standard ISO 50 surface determination protocol to visualize this. A Nikon XTH 225 (Nikon Metrology, Tring) industrial CT was used to analyse the pores/ defects' location and volume.

Defects of between 50 and 1400 microns in diameter were machined into the surface of the designed artefact using a CNC machine equipped with micro-drills. Once this was achieved, the defects were characterized using a Alicona G4 (Alicona, Graz) focus variation instrument. Data processing, surface determination process and defect analysis was carried out using VG Studio Max 3.1 (Volume Graphics, Heidelberg).

The focus of the study is on providing best practice guidance regarding the selection of inspection parameters and identifying the capability of ISO 50 surface determination in detecting unfused powder.



AlSi10Mg alloy powder 5-20µm used in SLM process

2<sup>nd</sup> – 3<sup>rd</sup> July 2018 University of Nottingham



# Automated measurement calibration for more accurate metrology in existing micro-CT systems

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#### Abstract

A variety of system alignment imperfections can affect measurement accuracy in CT scans. However, as magnification increases, the error caused by uncertainty in the X-ray source Focus-to-Object Distance (FOD) becomes dominant. Manipulator backlash, nonlinear or non-orthogonal axes, X-ray source thermal expansion among other effects can all affect the FOD. At the high geometric magnifications commonly used in micro-CT systems, this error becomes so large that errors from other minor misalignments become negligible.

One solution is to build a system with an extremely rigid, precision-aligned sample manipulator, with encoder readout on all translational axes, along with other enhancements. This not only reduces errors caused by other misalignments (for example Focus-to-Imaging distance, detector squareness, etc.) but, crucially, also provides a significantly more accurate FOD. This however results in an increased cost, and cannot easily be retrofitted to existing systems.

A solution for current systems is to calibrate the FOD for each scan by scanning a calibration artefact. This dramatically reduces uncertainty in the FOD, and therefore results in more accurate dimensions in the scan. This is traditionally a manual process with multiple steps, each of which is prone to user error. It is particularly notable that if multiple samples are scanned with the same manipulator position, the user must remember to apply the calibrated FOD to each subsequent scan. We present the use of automated FOD calibration, in which the only user step is to insert a calibration artefact; this is then automatically scanned, reconstructed and analysed, and the FOD corrected for multiple scans carried out in the same position.

#### 2<sup>nd</sup> – 3<sup>rd</sup> July 2018 University of Nottingham



# The TomoSynth module for the simulation of complex and noisy scanning trajectories in aRTist

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#### Abstract

Simulation becomes more and more important in modern CT imaging. It is increasingly used to optimize techniques for complex applications, to support the preparation of written procedures, and for educational purposes. The radiographic simulator aRTist is a modelling tool which simulates X-ray imaging using a hybrid analytical and Monte Carlo method to efficiently model the radiation transport. In addition to the relevant physical effects such as absorption, scattering and fluorescence, simplified fast models are employed to describe the characteristics of the X-ray source and the detector. aRTist is well equipped to model realistic X-ray imaging setups due to the ability to load exported CAD object descriptions. A simple CT scan module is contained in aRTist which allows the simulation of standard (circular cone beam) scanning trajectories.

TomoSynth is a module for aRTist which allows to set up more complex scanning trajectories by attaching geometrical modification functions to the objects in the radiographic scene. In this way, advanced scanning modes can be realized, for instance helical CT as an overlay of a rotation and a linear motion, or laminography as a motion of the source point. In addition to deterministic motion, also random variations can be introduced. By combining random variations with deterministic motion, non-ideal (realistic) CT scan geometries can be simulated, e.g. focal spot drift and mechanical instability of the axis of rotation. The TomoSynth module conveniently allows to construct these scenarios in a graphical interface and provides a preview before starting the (potentially long running) batch job. Therefore, deviations from ideal CT scan trajectories can be easily adjusted which is a necessary step towards uncertainty determination from simulation.



Simulation of Helical CT with TomoSynth and aRTist



#### 2<sup>nd</sup> – 3<sup>rd</sup> July 2018 University of Nottingham

# Analysis of strut bending defects in additively manufactured lattice structures by X-ray computed tomography

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#### Abstract

X-ray computed tomography (XCT) is an effective tool for examining complex structures, which is particularly advantageous for additively manufactured lattice structures. Lattice structures are produced mainly by powder bed fusion, a process known for introducing high residual stresses into its parts due to the high processing temperature. Defects in lattice structures include sagged/warped struts, porosity, broken struts and high surface roughness. These defects have a higher impact on lattice structures than bulk parts due to the small dimensions of lattice cells. In this work, we used XCT to measure a strut-based body centred cubic lattice structure (Figure 1) and examined strut bending defects, which affect mechanical properties of the part such as compressive strength and natural frequency. These properties are important in precision engineering applications where lattice structures are used, for example, as support frames for measurement instruments to provide vibration damping. A Nikon MCT225 XCT system has been used to provide quantified data on the form and dimensions of the bending defects in a laser sintered nylon-12 structure. However, the commonly used deviation map cannot accurately describe the bending of individual struts as the displacement of nodes is not taken into consideration. Therefore, a dedicated method has been developed to extract individual struts and determine the amount of bending. Future work will implement the observed bending defects into the CAD model and use numerical simulations to investigate the effect of strut bending on the structure's compressive strength and natural frequency.



Figure 1 – Bending defects in a body centred cubic lattice structure. 2 x 2 x 2 configuration

2<sup>nd</sup> – 3<sup>rd</sup> July 2018 University of Nottingham



# TomoPhantom: software package to generate 2D–4D phantoms for CT image reconstruction algorithm benchmarks.

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#### Abstract

This poster describes the use and launch of TomoPhantom; a software based phantom generation toolkit. Within CT imaging many novel reconstruction techniques are routinely tested using simplistic numerical phantoms. This package has been needed for a long time across user groups; and it now allows users to have quick access to an external library to create advanced modular analytical 2D/3D phantoms with temporal extensions. Code has just been released and available at https://github.com/dkazanc/TomoPhantom as well as published in a use case paper in SoftwareX.

2<sup>nd</sup> – 3<sup>rd</sup> July 2018 University of Nottingham



# X-ray CT: Image Reconstruction Frameworks Software Working Together.

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#### Abstract

This poster describes the EPSRC networking exchange process involved in the early stages of integrating two different dataflow frameworks together. The Core Imaging Library framework for 3D and 4D reconstruction of CT data is a set of modules for each process involved in the data analysis workflow – part of the Collaborative Computational Project in Tomographic Imaging for the UK tomography community. And the Tomviz Framework in the USA by Kitware Inc. carries out three-dimensional characterization of materials at the nano- and meso-scale using transmission and scanning transmission electron microscopes (S/TEM) data. To incorporate X-ray CT data set within these frameworks transparently a virtual merge of the UK / USA Research Software Engineer (RSE) has been initiated so that experience, best-practice, code and examples can all be shared.

#### 2<sup>nd</sup> – 3<sup>rd</sup> July 2018 University of Nottingham



# Determination of measurement uncertainties of holes in steel components by X-ray computed tomography

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#### Abstract

Due to the technical progress, X-ray computed tomography (CT) can be used not only in the field of non-destructive testing, but also in the field of dimensional metrology. Overall process of CT measurement is complex and involves many factors, such as those related to CT setup together with influence of CT operator, as well as various properties of the sample under investigation. Both analytical and simulation approach to uncertainties determination requires knowledge of all important parameters and their influence on CT measurement. In this work, we have determined uncertainties according to the standard VDI/VDE 2630 2.1, which is based on the comparison of CT measurement with reference measurement. A hollow stainless steel stepped cylinder (Fig. 1) Fig. 1 was manufactured in order to find a dependence of measurement uncertainties of inner and outer

diameters on the cross-sectional material thickness. The reference dimensions were determined using length measuring machine SIP 1002 M. Consequently, several measurements with the same settings were performed on the GE phoenix v|tome|x L240 microCT device. The uncertainties of inner and outer circular diameters were calculated for two settings of surface determination. Circles were fitted at different heights on cylinder (Fig. 1).

The uncertainty of inner diameters increases with material penetration length. Surface determination in the bottom part of the sample is affected by the noise, which is one of the main contributors of the uncertainty. The relative uncertainty of outer diameters slightly decreases with penetration length.

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Fig. 1: Longitudinal CT cross-section of stainless steel stepped cylinder. Red lines show positions of the inner and outer diameter measurement.

#### 2<sup>nd</sup> – 3<sup>rd</sup> July 2018 University of Nottingham



# Synchrotron X-ray micro Computed Tomography of fossils preserved on slab.

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#### Abstract

Palaeontologists have become regular users of X-ray computed tomography (CT) facilities to study fossils in a non-destructive way. Beyond the conservation aspect, X-ray CT offered the possibility to study samples in 3 dimensions, gaining extra information. The use of synchrotron radiation as a source was driven by specific characteristics. The brilliance, parallel geometry, and coherence of the beam participate in opening new opportunities compared to laboratory sources. While at its debut, synchrotron light source experiments focussed on small fossils, the development of optics allowing for horizontal field of view up to 25 cm gradually introduced larger specimens. Projects awarded for beamtime are now often based on pristinely preserved fossils, promising a high potential for results. These wonderful fossils are often preserved on slabs, a geometry for which X-ray CT is ill-suited. To overcome the problem several protocols have been tested at the ESRF to improve quality during the acquisition. For instance the so-called attenuation protocol was successfully tested on many important specimens. Consisting of plunging the sample in a tube filled with small aluminium or glass balls, with the benefit of homogenising the attenuation throughout the acquisition. However, putting delicate specimens in contact with these materials proved dangerous. Large accumulation factor for each projection and filtered white beam are now preferred allowing for usable signal-to-noise ratio on projections along the width of the slab. Post-experiment processing have also being developed, notably keeping at least 50 % of overlap between radiograph along the vertical axis, using the duplicate information to facilitate ring artefact correction. Finally, while the increase of the horizontal field of view was principally done using an offset in the centre of rotation, multiple lateral concatenations of reconstructed tomograms is now preferred, facilitating the reconstruction process and focussing the production of data on the slab itself.



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