
# Dimensional X-ray Computed Tomography Conference 2017

The Slate, University of Warwick
13 July 2017

NPL
National Physical Laboratory

WMG
THE UNIVERSITY OF WARWICK

# Welcome

The organising committee takes great pleasure in welcoming you to the second NPL Dimensional X-ray Computed Tomography (dXCT) conference, this year hosted by WMG, University of Warwick.

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. The companies' exhibits are available during the breaks to discuss their recent software and hardware developments. In addition, we would like to thank both NPL, FEI and Synopsys for providing software 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 the HVM Catapult and WMG 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 Warwick.

**The Organising Committee**

# Useful information

## Wireless access

Connect to "Warwick Guest" wireless network and follow the instructions. An "eduroam" network is also available.

## Social media

We encourage you to share the conversation on social media using **#dxct2017** or by following our sponsors **@WMGWarwick** and **@NPL**, and exhibitors:

**@Aegleteq** **@blue_scientific** **@HVM_Catapult** **@FEI_Global** **@generalelectric**

**@HamamatsuPhoton** **@LaVisionInc** **@UKNikon** **@Synopsys** **@ZEISS_Group**

# Programme

| | |
|---|---|
| **09.00** | **Registration/Coffee** |

## Session 1: Acquisition and process methodologies

Session Chair – Jay Warnett

| | |
|---|---|
| **10.00** | Introduction<br>*Alex Attridge; University of Warwick* |
| **10.15** | Limited view X-ray CT for dimensional analysis<br>*Glenn Jones; Imperial College London* |
| **10.35** | A versatile laminographic scanning system as an additional for an existing CT scanner<br>*Thomas Blumensath; University of Southampton* |
| **10.55** | A study into the use of simple holeplates to measure the apparent distortion in the geometry of reconstructed volumes<br>*Hannah Corcoran; UCL/NPL* |
| **11.15** | Coffee |

## Session 2: Industrial development and application

Session Chair – Martin Turner

| | |
|---|---|
| **11.35** | XCT measurement applications in aerospace<br>*Kevin Pickup; BAE Systems* |
| **11.55** | Dimensional 3D X-ray Computed Tomography at high absorbing samples<br>*Thomas Mayer; GE Oil and Gas* |
| **12.15** | Additional problems with CT metrology for large samples<br>*David Bate; Nikon* |
| **12.35** | Lunch |

## Session 3: Applications of CT measurement

Session Chair – Richard Leach

| | |
|---|---|
| **13.30** | Tracking the evolution of a defect characteristic of AFP layup during cure with in-process micro-XCT scanning<br>*Laura Pickard; National Composites Centre/University of Bristol* |
| **13.50** | Automated processing for 3D powder characterization<br>*Parmesh Gajjar; University of Manchester* |
| **14.10** | A sensitivity analysis for the measurement of internal additively manufactured surfaces by X-ray Computed Tomography<br>*Adam Thompson; University of Nottingham* |
| **14.30** | Detection of unmelted powder in additive manufactured components using Computed Tomography<br>*Ahmed Tawfik; University of Huddersfield* |
| **14.50** | Coffee |

## Session 4: Accuracy and standardisation

Session Chair – Wenjuan Sun

| | |
|---|---|
| **15.10** | Operator influences on CT scanning: a round robin study<br>*Jay Warnett; WMG, University of Warwick* |
| **15.30** | Verifying the dimensional performance of XCT systems with metrology capability<br>*M. McCarthy; BSI/Engineering Metrology Solutions* |
| **15.50** | Panel discussion |
| **16.20** | Conference close |
| **16.35** | Lab tour (optional) |

# Session 1: Acquisition and process methodologies

## Session Chair – Jay Warnett

### Limited view X-ray CT for dimensional analysis

**G. A. Jones** and P. Huthwaite
*NDT Group, Imperial College London, South Kensington, London, UK.*

The increasing use of complex and irregularly shaped components for safety-critical applications has led to the increasing adoption of X-ray CT as an NDE inspection tool. X-ray CT enables 2D and 3D images of the internal features of the object to be computed and subsequently subject to dimensional analysis. However, standard X-ray CT methods require thousands of projections, each regularly distributed evenly through 360° to produce an accurate image. The large number of projections and the regularity of sampling can result in lengthy data acquisition times and can lead to bottlenecks in manufacturing throughput. To alleviate these bottlenecks in throughput companies may be forced to purchase additional X-ray CT capability at great cost.

In recent years there has been a drive by the medical industry to reduce patient X-ray exposure by limiting the number of projections whilst maintaining image quality in CT applications. Spurred by the ever increasing power of computers and the advent of graphics card processors, a variety of limited view tomographic techniques capable of generating high quality images with less data have been developed. Central to these new algorithms is the principle of compressed sensing, whereby an understanding of the signal sparsity is exploited to produce accurate reconstructions of the signal of interest with fewer samples than those required by the Shannon-Nyqist theorem. We present a survey of limited view algorithms for x-ray CT of a turbine blade with the aim of producing accurate internal structure estimates using minimal data.

### A versatile laminographic scanning system as an addition for an existing CT scanner

N. S. O'Brien[1], C. E. Wood[2], and **T. Blumensath**[1,2]
[1]*mu-VIS X-Ray Imaging Centre, University of Southampton, University Road, Southampton, SO17 1BJ*
[2]*ISVR, University of Southampton, University Road, Southampton, SO17 1BJ, UK*

There is increasing interest in performing 3D scans of specimens whose large aspect ratios mean they are ill-suited to conventional computed tomography (CT) for non-destructive testing, inspection and quality-control purposes. There is increasing demand for methods to identify both defects arising during manufacture, and damage sustained during the life-cycle of the parts. Various techniques may be applied when X-ray scanning such specimens, including variable energy or variable exposure CT scanning, and laminographic scanning using non-standard trajectories. We have designed and built a demonstrator allowing for the implementation of a range of trajectories other than traditional full rotation CT to perform region-of interest laminographic scanning on large planar specimens within an existing, custom bay CT scanner located at the University of Southampton. Here we give an overview of key aspects of the system and present initial results from scanning carbon fibre reinforced polymer (CFRP) panels, as may be applied in a non-destructive testing scenario.

### A study into the use of simple holeplates to measure the apparent distortion in the geometry of reconstructed volumes

**H. Corcoran**[1,2], S. Brown[2], S. Robson[1], R. Speller[1], M. McCarthy[1], W. Sun[2]
[1]*University College London, Gower Street, London, WC1E 6BT, UK*
[2]*National Physical Laboratory, Hampton Road, Teddington, TW11 0LW, UK*

X-ray computed tomography (XCT) is being used extensively for dimensional measurements in an industrial and manufacturing setting. The use of a complex aluminium holeplate to measure the effects of beam hardening on unidirectional and bidirectional lengths has been studied before by other authors and is central to an emerging ISO standard. Previous work by the authors has highlighted the presence of significant deformations in the surface of reconstructed holeplate cylindrical holes of the order of up to 60 µm. In order to better understand the physical reasons for these deformations the authors have investigated a series of simple holeplates.

This paper presents work focusing on three simple holeplates that have the same 48 mm x 48 mm x 8 mm dimensions and 4 mm hole radius as the original holeplate but have only one hole in them, the position of which varies for each holplate. These holeplates were used to measure the apparent distortion of the geometry of the reconstructed holes. The holeplates were measured at varying angles and magnifications.

Results demonstrate that the orientation of the holeplate on the manipulator affects the geometry of the reconstructed cylindrical holes. In all reconstructions, systematic deviations from a perfect cylinder in the computed hole radius of between -65 μm to 20 μm were found. Results indicate that the perceived distortion of the hole is related to the amount of material the X-rays have travelled through, which in turn is related to the attenuation of the polychromatic X-ray beam and therefore beam hardening. This theory was confirmed with the manufacture and imaging of a circular holeplate, which when imaged horizontally, demonstrated only the random (±10 μm) measurement perturbations expected from the system being tested. This work is important not only in considering the use of a holeplate as an ISO reference but also to the general case of XCT for high accuracy dimensional metrology where voids in dense materials are being imaged.

# Session 2: Industrial development and application

## Session Chair – Martin Turner

### XCT metrological applications in aerospace

**K. Pickup**
*BAE Systems, Preston, PR1 8UQ, UK*

As manufacturing evolves within the aerospace world, the real challenge is often proving to the legislator that the part was made correctly with sufficient integrity to cope with its intended design environment. This applies to the finished product and for every process involved in making the product to ensure repeatable, efficient manufacturing. To assist in this, X-ray Computed Tomography is starting to play a key role. XCT can reach places that traditional tactile systems simply cannot go and often extends the Region of Interest (ROI) with increased data mining providing superior Statistical Process Control (SPC).

As we expect greater performance of our materials and designs in terms, every anomaly must be analysed to ensure the part is fit for flight. XCT allows us to 3D map the location and topology of indications, the data from which can then be used in accurate simulations of the part or simply to form a digital twin – which is becoming the manufacturing standard.

As well as new product assessment, we are using XCT for metrological assessment of failed items to improve understanding of failure modes and provide an undisturbed view of the failure. Finally, with the increased use of Additive Manufacturing (AM) in aerospace, XCT is proving invaluable assisting with design iteration and final product inspection.

### Dimensional 3D X-ray Computed Tomography at High Absorbing Samples

**T. Mayer**
*GE Oil & Gas - Digital Solutions, Niels-Bohr-Str.7, 31515 Wunstorf, Germany*

Computed Tomography (CT) becomes the technology of choice for nondestructive testing and more and more for metrology tasks, e.g. for automotive castings, aerospace turbine blades or 3D printed parts. For 3D metrology, a major challenge is the measurement of hidden features. Increased cycle time requirements combined with a high inspection depth require improved methods to deal with imaging artefacts.

Scattering of X-rays is the main factor for such artefacts in conventional cone beam CT. While state of the art scatter reduction simulates scatter based on CAD data or sample's material properties, the new method is really measuring the scatter portion of that specific sample in the CT scanner and minimizes it from the CT result for every individual voxel. Dimensional metrology of 3D cone beam CT scans becomes possible because the sample edges in the volume are detectable like in CT scans generated with up to hundred times slower fan beam CT.

In the presentation, the influence of advanced scatter correction technology on 3D measurements will be shown.

Considering the fact that 3D metrology with CT always uses automatic surface detection algorithms to determine the surface of the 3D volume to measure, compared to conventional cone beam CT the new method allows more material penetration (up to 30%) at the same scan parameters to still determine the exact surface. At same material penetration length, the new scatter correction method allows a more precise surface detection due to less artifacts negatively affecting the metrology results.

### Additional problems with CT metrology for large samples

**D. Bate**
*Nikon Metrology UK, Icknield Industrial Estate, Herts, HP23 4JX, UK*

There is a lot of effort underway worldwide to characterise the use of X-ray Computed Tomography for metrology of parts in a way similar to the more traditional tactile CMMs and optical techniques.

Much of this work is happening at X-ray energies < 225 kV and also on low to medium density samples (Plastics, Aluminium) or small samples of higher density. While there are a number of issues that need to be resolved (Beam hardening, cone beam artefacts (with FBP) or similar reconstruction effects) these will be present at all energies.

As we try and expand the technique into larger samples there are two key issues that will be discussed in this paper:

1. Penetration: In order to scan larger parts a combination of higher flux and higher energy are required to give enough detected X-ray flux to give high quality CT data. This paper will discuss the approach of using minifocus sources for greater flux and the use of Novel high energy microfocus sources to overcome this issue (including the new facility being developed here in Warwick)
2. Scattering: As the energy of the X-rays increases and the density of the samples increases the contribution of scattering to the noise increases, this leads to a SNR issue if not handled. This paper will look at techniques to either reject the scatter or to correct for the scatter errors

As can be seen at the < 225 kV energies used traditionally the dominant scatter mechanism is coherent scatter and this introduces little noise to the image, but as the energy increase past about 400 kV the Compton scattering (incoherent) becomes the dominant mechanism and this lead.

# Session 3: Applications of CT measurement

## Session Chair – Richard Leach

### Tracking the evolution of a defect characteristic of AFP layup during cure with in-process micro-XCT scanning

**L. R. Pickard**[1,2], K. Smith[2], J. Kratz[2], K. Potter[2]
[1]*National Composites Centre, Bristol & Bath Science Park, Emersons Green, Bristol, BS16 7FS, UK*
[2]*University of Bristol, Tyndall Avenue, Bristol, BS8 1TH, UK*

Micro-XCT scanning is often used for inspection of composite materials to identify defects and damage. A defect which occurs early in the manufacturing process may change as the composite item is cured, by application of heat and pressure or vacuum. An increased understanding of how these defects change during the cure process can inform design and manufacturing process choices. This paper presents the detailed evolution of a deliberate gap in the composite, throughout the cure process, using a novel setup for In-Process Micro- X-ray CT.

A Nikon XTH-320 industrial CT scanner using a 225KeV reflection target was equipped to allow heating- and hence curing- of an uncured sample under vacuum. Short scans at of approximately 7 minutes, with 1600 frames per projection at 250ms exposure, were performed repeatedly at 180KeV, as a batch program during cure. VG Studio Max was used to perform a void analysis on a set region of interest for each scan, tracking the changes over time.

Here we discuss the evolution of a cylindrical sample of carbon fibre sheets pre-impregnated with an epoxy resin, containing a 2 ply thick 2mm gap across the centre. The evolution of the gap is compared to the theoretical resin behaviour. In-process micro- X-ray CT has the potential to provide far more detailed information on the behaviour of composites during cure than has been available prior to today. This work provides both proof of the principle, as an experimental method, and shows detailed results measuring the evolution of a gap during the cure of carbon fibre prepreg materials.

### Automated processing for 3D powder characterization

**P. Gajjar**, J. Carr, J. Behnsen, P. J. Withers
*University of Manchester, Oxford Road, Manchester M12 9PL*

The quantitative geometric characterization of powders from sub-micron to micron length scales can be achieved through a wealth of techniques. These include light scattering, diffraction, 2D imaging as well as sieving and sedimentation methods to estimate, for example, particle size and shape distributions. However, all of these techniques prove to be of limited use for complex powders in which 3D features such as shape, coatings and internal porosity are important.

We present a method for utilizing X-ray microtomography (µCT) for obtaining the true 3D geometry of powders at multiple length scales. This information can be used to generate accurate size and shape distributions as well as quantifying multiple phases. An automated workstream was also developed for processing 3D image datasets to produce repeatable and reliable results for quantitative powder characterization.

This scope of µCT for characterisation is demonstrated for a range of different powder types from coarse civil aggregates and metallic powders to common household detergents. In addition, µCT characterisation of fine lactose crystals that are used as excipients in inhaled therapies gives invaluable insights into the different milling and processing techniques used during the formulation manufacturing. Additive manufacturing, pharmaceuticals and paint processing are just three of many potential applications that could harness the 3D characterisation ability of XCT, with opportunities across multiple industrial fields.

### A sensitivity analysis for the measurement of internal additively manufactured surfaces by X-ray Computed Tomography

**A. Thompson**[1], N. Senin[1,2], I. Maskery[1], L. Körner[1], S. Lawes[1], R. Leach[1]
[1]*Manufacturing Metrology Team, University of Nottingham, Nottingham, NG7 2RD, UK*
[2]*Department of Engineering, University of Perugia, 06125, Italy*

Recent studies have shown that X-ray computed tomography (XCT) can be used for the measurement of internal and otherwise difficult-to-access surfaces that have previously been considered unmeasurable, for example, those commonly present on complex additively manufactured (AM) parts. However, investigations into the sensitivity of XCT instruments to measurement process control parameters, when the measurement is directed towards the acquisition of topographic information at microscopic scales, are yet to be undertaken. In this work, the effects of geometric magnification and reconstruction sampling in XCT surface topography measurement are examined. A hollow Ti6Al4V artefact fabricated by laser powder bed fusion is used as a test case. Topographies obtained by varying XCT measurement parameters are compared through the use of novel statistical topography modelling methods combined with the use of industrially-established surface topography descriptors (areal texture parameters). XCT topographies are also compared to reference results acquired using focus variation microscopy and coherence scanning interferometry instruments.

### Detection of unmelted powder in additive manufactured components using Computed Tomography

**A. Tawfik**, R. Racasan, P. Bills, L. Blunt
*EPSRC Future Advanced Metrology Hub, University of Huddersfield, Huddersfield, UK*

Additive manufacturing (AM) is recognized as a core technology for producing advanced high value components. The possibility of producing complex and individually modified components as well as prototypes gives additive manufacturing a substantial advantage over conventional subtractive machining. One of the current barriers for most industries in implementing AM is the lack of build repeatability and a deficit in quality assurance standards. The mechanical properties of the components depend critically on the density achieved therefore defect/porosity analysis must be carried out to verify the components' integrity and viability.

This paper presents a methodology for differentiating between unmelted powder and defects/pores in additive manufactured components using computer tomography thus allowing the detection of pores even when they are "filled" with unmelted powder. The powder used was Ti6AL4V with a grain size of 45-100µm, typically employed with Arcam electron beam melting (EBM) machines. The samples consisted of a plastic test tube filled with powder and a known volume small plastic particles that were placed inside acting as pores/defects. A Nikon XTH 225 industrial CT was used to measure the samples to detect the pores/defects locations and volumes.

To reduce the number of process variables, the measurement parameters, such as filament current, acceleration voltage and X-ray filtering material and thickness are kept constant. VgStudio Max 3.0(Volume Graphics, Germany) software package was used for data processing, surface determination and defects/ porosity analysis. The impact of surface determination on the results, repeatability and accuracy are discussed. The main focus of the study is exploring the optimum methods to enhance the detection capability of pores/defects filled with powder using computer tomography.

# Session 4: Accuracy and standardisation

## Session Chair – Wenjuan Sun

### Operator influences on CT scanning: a round robin study

**J. M. Warnett**[1], A. Attridge[1], N. Brierly[2], R. Van Gelder[3], L. Ashton[4], M. A. Williams[1]
[1] *WMG, University of Warwick, Gibbet Hill Road, Coventry, CV4 7AL, UK*
[2] *MTC, Ansty Park, Coventry, CV7 9JU, UK*
[3] *National Composites Centre, Bristol and Bath Science Park, Emersons Green, Bristol, BS16 7FS, UK*
[4] *AMRC, Advanced Manufacturing Park, Wallis Way, Catcliffe, Rotherham, S60 5TZ, UK*

XCT is widely used in high value manufacturing applications as it can provide information on internal and external geometries, identification of porosity and location of defects. Numerous authors have demonstrated its capability as a dimensional measurement tool, quantifying errors often smaller than the voxel size itself. Aside from source/detector variations and geometric errors, the operator has a significant influence on the results through parameter selection. Current standards available from BSI, ASTM and VDI/VDE offer general guidance on the operation of an XCT scanner and how different parameters can affect the results, but missing is a generic workflow on how one should setup a scan. This inevitably leads to a degree of variability between resultant data that impacts dimensional results.

In this study two work pieces, one polymer and one metallic, were used with several measurands identified that were initially measured using a CMM as a reference measurement. All the centres had a similar CT system (variation of Nikon 225) on which they initially scanned the object, selecting their own parameters. The data was reconstructed using the same settings, evaluated in VG studio using a standard surface determination and dimensioned according to measurements obtained by CMM. Without voxel scaling, the variation due to geometric error dominates resulting in deviations to the order of 10's of voxel compared to CMM measurements. After voxel scaling, errors are reduced to the order of sub micron, but there is still some relatively large variations between centres. It is difficult to de-couple the impact of individual parameters while it is known they must have an effect. To demonstrate this, a second round robin of the work pieces were complete where operators scanned with prescribed parameters. Here it was observed that the variation between centres was reduced by at least 50% compared to operators own selection. This result in its own right demonstrates the need for a more standardised workflow for operators to follow so uncertainty in XCT measurement can be accurately described.

## Verifying the dimensional performance of XCT systems with metrology capability.

**M. McCarthy**
*BSI*

Michael McCarthy is an honorary Professor at University College London (UCL) and Lead Consultant at 'Engineering Metrology Solutions' (EMS). He chairs BSI's Technical Product Realization (TPR/1/4) panel for XCT and is a principle member of the ISO TC213 working group for XCT. His presentation will provide an overview of the current draft XCT document ISO 10360 part 11 which was released for review in March 2017.

Many published parts of the ISO 10360 series are well established, covering the acceptance and reverification of coordinated measuring systems employing both tactile and optical probing systems. However, the ISO 10360 part 11 under development is being designed to specifically focus on supporting metrology systems using the principle of computed tomography (CT). The internationally agreed intention of this proposed XCT addition to ISO 10360 series is to achieve comparability with the characteristics of other coordinate measuring systems employing tactile or optical sensors. Some of the comparability issues and the resultant challenges they present will also be discussed.

# Poster Presentations

### Characterisation of CT noise in projection and image space with applications to 3D printing

**S. Ip**[1], A. Kueh[1], J. M. Warnett[2], G. Gibbons[2], M. A. Williams[2], T. Nichols[1], W. Kendall[1]
[1]*Warwick Statistics, University of Warwick, Coventry, CV4 7AL, UK*
[2]*WMG, University of Warwick, Coventry, CV4 7AL, UK*

X-ray CT can be used in defection detection for 3D printing. The object is scanned at multiple angles to reconstruct the object and any defects in 3D space. The process can be time consuming. To speed up the process it may be possible to conduct defect detection in projection space from a single scan. X-ray photons behave randomly, they arrive at a Possion rate with random energy. Hence to do defect detection pixel by pixel, uncertainty must be taken into account. One way is to model the greyvalue of each pixel as a compound Possion random variance to capture the behaviour of x-ray photons. This results in a linear relationship between the mean and variance of the greyvalue, which can be used for variance prediction. Methods for multiple hypothesis testing, when testing each pixel for defects, must consider dependencies between pixels. One way to test this is to estimate the spatial autocorrelation and it was investigated whenever shading correction would also correct correlation between pixels.

### Revealing the complex metal carbide morphologies of cast Ni superalloy by synchrotron X-ray microtomography

**B. Koe**[1, 2], J.C. Khong[1, 3], N. Green[4], A.J. Bodey[2], Z. Zhang[5], J. Gebelin[5], C. Rau[2], J.Mi[1]
[1]*School of Engineering & Computer Science, University of Hull, Hull HU6 7RX, UK*
[2]*Diamond Light Source Ltd, Harwell Science and Innovation Campus, Didcot OX11 0DE, UK*
[3]*Department of Medical Physics & Biomedical Engineering, University College London, London WC1E 6BT, UK*
[4]*High Temperature Research Centre, University of Birmingham, Birmingham B15 2TT, UK*
[5]*Doncasters Group Technical Centre, George Baylis Rd, Droitwich WR9 9RB, UK*

Nickel-based superalloys are widely used in the aerospace industry, particularly in high temperature applications, due to its' exceptional high-temperature strength, toughness, creep properties, and resistance to degradation in corrosive and oxidising environments. Metal carbides are essential structural features for improving the high-temperature creep properties of these superalloys. Although the structures and morphologies of these metal carbides were widely studied in the past by using electron microscopy techniques, the true 3D morphology of these metal carbides have not been reported. In this study, we used synchrotron X-ray microtomography, at the Diamond-Manchester Imaging Beamline (I13-2), Diamond Light Source, UK, to reveal the influence of solidification time on the true 3D morphology and the complex network of metal carbides formed during the casting of a widely used IN713LC Ni superalloy. In order to maintain the high fidelity tomography datasets, the visualisation nodes of the University of Hull's newly established high performance computer (Viper) were utilised to perform the graphics-intensive visualisation.

### The effects of continuous scan motion on surface measurement by X-ray Computed Tomography

**L. Körner**[1], A. Thompson[1], N. Senin[1, 2], S. Lawes[1] and R. Leach[1]
[1]*Manufacturing Metrology Team, University of Nottingham, UK*
[2]*Department of Engineering, University of Perugia, 06125, Italy*

X-ray computed tomography (XCT) has recently gained attention as a tool for surface metrology. Particularly, XCT's ability to measure internal features allows for non-destructive surface metrology of additively manufactured (AM) parts. While initial investigations have proven the feasibility of XCT for surface texture measurement, the various factors that influence XCT measurements have not yet been explored in depth. The parameter space of XCT measurements is large: the current guideline document VDI/VDE 2630-1.2 lists over sixty variables. Amongst such variables, the number of projections has been of frequent interest to the XCT community. For practicality and speed, continuous scanning, i.e. measurement with continuous rotation of the sample, is commonly used. With continuous scanning, projection data is averaged over a span of angular positions. The work presented in this paper explores the effects of changing the number of projections while operating in continuous scanning mode. A cubic sample of (10 × 10 × 10) mm, manufactured on a Realizer SLM 50, using a sieved Ti6Al4 powder to limit the grain size to below 32 μm, is scanned on a 225 kV source cone beam XCT system, with the longest dimension, the diagonal, in line with the axis of rotation. The number of projections and therefore the angular averaging of the projection data is varied. For each condition surface data are extracted using VGStudio MAX 3.0 and exported as triangulated models. These are raster-scanned into digital elevation models for calculation of areal surface texture parameters in MountainsMap. Surface topography results corresponding to each XCT measurement configuration are assessed through summary indicators such as texture parameters (e.g. those defined in ISO 25178-2). Texture parameter results are compared to the topography measured with a focus-variation microscope.

### The life and death of pixels

**J Brettschneider**[1], C Barnes[2], J Warnett[3], G Gibbons[3], M Williams[3], T Nichols[1,3], W Kendall[1]
[1]*Warwick Statistics, University of Warwick, Coventry, CV4 7AL, UK*
[2]*Department of Statistical Science, University College London, London, WC1E 6BT, UK*
[3]*WMG, University of Warwick, Coventry, CV4 7AL, UK*

While there are obvious global measures to quantify the amount of damage in an X-ray detector, natural questions also arise around the spatial distribution of the dysfunctional pixels and how observed patterns of dysfunctional pixels may be interpreted. After modelling occurrences of dysfunctional pixels as a planar point process we develop a higher level approach for analysing their spatial distributions. Key idea is to move from the notion of a dysfunctional pixel to the concept of a damage event defined by configurations of dysfunctional pixels using a typology based on local grid geometry. High density regions can be detected using density estimation of the damage event process, so remaining areas becomes suitable candidates for complete spatial randomness. This approach decouples observed damage from the detector resolution prescribed by I and from the exact shape of dysfunctional pixel configurations. We proposes a detector quality toolkit that allows users to monitor their technology following these principles. The methods allow users of detector based imaging technologies to detect, distinguish and monitor different types of quality damage and to identify the ones linked to specific causes. We apply our methods to a collection of bad pixel maps obtained as part of regular monitoring routines of a detector used in X-ray computed tomography.

### A novel surface characterisation strategy for the X-ray Computed Tomography measurement of complex additively manufactured parts

**S. Lou**, W. Zeng, H. Abdul-Rahman, X. Jiang, P. J. Scott
*EPSRC Future Metrology Hub, University of Huddersfield, Queensgate, Huddersfield, HD1 3DH*

X-ray Computed Tomography (XCT) has the advantage over the traditional tactile and optical measurement systems in that it is the only valid non-destructive method to measure both external and internal geometries of complex functional parts, e.g. additively manufactured (AM) parts, whose intricate shape does not allow line-of-sight. However the XCT measurement posts many challenges to surface texture assessment of AM parts. One of the big issues is that XCT generated measurement data structures, i.e. point cloud and triangular mesh, are not straightforward compatible with the standard surface texture characterisation, which requires uniform sampled grid structure and also requires measured surface to be basically planar. This work proposes a novel strategy that the surface filtration and roughness parameterisation techniques can deal with triangular mesh. Based on the link between the Gaussian cutoff wavelength and the diffusion time, the proposed linear diffusion equation can achieve a Gaussian filtering effect on complex surfaces. Also the areal surface texture height parameters are extended to triangular mesh. With these two enhancements, it contributes to the solution to using XCT for a holistic and reliable measurement of surface texture of complex AM products.

### XCT for forensic engineering and failure analysis

**N. Kourra**, J. M. Warnett, A. Attridge, M. A. Williams
*WMG, University of Warwick, Coventry, CV4 7AL*

Forensic engineering and failure analysis is a necessary process for development that demonstrates the required changes to evolve designs, material selection, manufacturing processes, operation guides and maintenance procedures. Interpretation of the facts and reasons for failures is achieved by examining the physical evidence, verifiable facts and utilising scientific principles, knowledge, skills and methodologies. Analysis by non-destructive and destructive testing provides conclusions explaining the failures and evidences routes to mitigation in the future through design alterations. X-ray Computed Tomography (XCT) is applicable in non-destructive evaluation and metrology, using a series of radiographs to generate 3D models of the examined objects. The greatest advantage of this technology is the representation of outer and inner structures of the examined objects that assist in the identification of abnormalities, defects that can lead to failures and hidden failures. This technology was used to investigate failures non-destructively and avoid the collection of reduced data by destroying part of the problematic areas. This study examines a series of different failures analysis and utilises volumetric analysis to examine any abnormalities and defects. The results demonstrate the application of CT in forensic engineering and failure analysis as a non-destructive test while they would be unobtainable with any other non-destructive method.

# Sponsors and Exhibitors

At Aegleteq we are here to provide you with the best possible solutions to all your Industrial radiographic and radioscopic requirements. We believe that Industrial X-Ray is a big enough field on its own which demands first class Client support in Sales and even more importantly in Service. So AEGLETEQ do not do Ultrasonics, Eddy Current, Hardness Testers, Film Sales and any other NDT discipline. Only X-ray Equipment, X-ray Systems and safety circuits.

We provide sales, Installation and support on the full range of YXLON International Industrial X-Ray equipment & Systems.

Blue Scientific provides a handpicked portfolio of market-leading scientific instruments for materials science, life science and energy research. Choose the right solution for your lab, with independent, expert advice.

Blue Scientific is the official UK distributor for Bruker micro-XRF, micro-CT and TD-NMR, Solartron, Princeton Applied Research, Physical Electronics, DELMIC and Protochips.

The HVM Catapult is the catalyst for the growth and success of UK advanced manufacturing. Our 7 centres offer access to world-class equipment, expertise and collaborative opportunities. We work with manufacturing businesses of all sizes and from all sectors, helping turn ideas into commercial applications by addressing the gap between technology concept and commercialisation.

WMG is one of seven centres that together comprise the High Value Manufacturing Catapult. The other centres are: Advanced Forming Research Centre (Strathclyde); Advanced Manufacturing Research Centre (Rotherham); Nuclear AMRC (Rotherham); Centre for Process Innovation (Wilton and Sedgefield); Manufacturing Technology Centre (Coventry); National Composites Centre (Bristol).

The WMG centre is addressing the challenge of low carbon mobility through R&D in Lightweight Technologies, Advanced Propulsion Systems, Energy Storage and Autonomous and Connected Systems. Working with transport sector partners in automotive, aerospace, commercial, off-road and rail, we are enabling and accelerating the development of new technologies, products and processes.

Collaborative Computational Project in Tomographic Imaging aims to provide the UK tomography community with a toolbox of algorithms that increases the quality and level of information that can be extracted by computer tomography. Chaired by Prof Philip Withers (University of Manchester); co-ordinated by staff in the Scientific Computing Department STFC; led by a working group of experimental and theoretical academics with links to Diamond Light Source, ISIS and Industry.

FEI
part of Thermo Fisher Scientific

With more than 60 years of innovation and leadership, FEI enables customers to find meaningful answers to questions that accelerate breakthrough discoveries, increase productivity, and ultimately change the world. FEI designs, manufactures, and supports the broadest range of high-performance microscopy workflows that provide images and answers in the micro-, nano-, and picometer scales.

Combining hardware and software expertise in electron, ion, and light microscopy with deep application knowledge in the materials science, life sciences, electronics, and natural resources markets, the worldwide FEI team of 2,700+ employees is dedicated to customers' pursuit of discovery and resolution to global challenges.

GE

GE Inspection Technologies: Advanced industrial Computed Tomography solutions for 3D metrology and failure analysis.

GE Inspection Technologies provides a full suite of non-destructive testing (NDT) solutions, including a wide range of industrial computed tomography (CT) systems from high-accuracy nanoCT up to gantry based helix CT for rapid industrial production process optimization. In casting, composite industry and especially in additive manufacturing, extremely complex parts with hidden geometries and failures require advanced non-destructive inspection and metrology technologies. With a bundle of GE proprietary patents and technologies like scatter|correct or high-flux|target as well as the exclusive industrial use of GE's dynamic 41 detectors, CT customers benefit from high precision results at high scan throughput. The specific metrology|edition allows a v|tome|x CT system even to be used for dimensional metrology referring to VDI 2630 guideline.

Based on its recent industrial computed tomography (CT) systems study, Frost & Sullivan has recently honored GE Inspection Technologies with the 2016 Global Industrial CT Company of the Year Award.

Learn more about GE's CT solutions for accurate and traceable CT metrology on www.gemeasurement.com/CT

HAMAMATSU
PHOTON IS OUR BUSINESS

Hamamatsu Photonics is a world-leading manufacturer of optoelectronic components and systems. The Company's corporate philosophy stresses the advancement of photonics through extensive research and yields products that are regarded as state-of-the-art. All products are designed to cover the entire optical spectrum and provide solutions for a wide variety of applications including analytical, consumer, industrial and medical instrumentation.

We will be displaying our range "X-ray Imaging" components, which include a wide range of technologies Microfocus X-ray sources and high resolution scintillators. In particular we will be exhibiting our sCMOS high resolution X-ray camera, which has been designed to be used within high resolution uCT applications.

## Sponsors and exhibitors

LaVision are a supplier of imaging systems and software including our StrainMaster Digital Volume Correlation (DVC) module.  DVC is a novel technique for full 3D strain and deformation measurements. The technique imports volume images of the component in reference and deformed states and is able to calculate the full 3D displacement and strain map. Images are typically acquired from X-ray Computed Tomography (X-ray CT) systems. Allows the user to identify sub-surface material deformation and is capable of pin-pointing defects, discontinuities, cracks or other material characteristics.  It is often used in for validation of FEA models.

As a supplier of innovative imaging systems and analysis software LaVision has established a strong reputation as a solutions provider among its customers from various industrial and academic research fields.  Application fields span a wide range including automotive, aerospace, power generation, biomechanics, civil engineering, and material testing.

Nikon Metrology's X-ray and CT portfolio originates from the UK based, X-Tek Systems. With an experience of more than 30 years, X-Tek has an extensive installation base of thousands of X-ray and CT inspection systems worldwide. CT specialists in Tring, UK, design, develop and manufacture complete systems, incorporating proprietary microfocus X-ray sources, high precision 5-axis fully programmable manipulators and extremely fast acquisition and reconstruction software.

Continuous development is an established goal, recent advances include high flux rotating targets, laminography, automatic radiographic image tone correction, high accuracy helical and offset CT.

From the 130kV system for inspection of electronics up to large configurable rooms with multiple detectors and multiple sources (including mini-focus), Nikon Metrology can offer the X-Ray/CT solution.

The National Physical Laboratory (NPL) is the UK's National Measurement Institute, and is a world-leading centre of excellence in developing and applying the most accurate measurement standards, science and technology available.

NPL develops and maintains the nation's primary measurement standards which underpin the National Measurement System infrastructure of traceability throughout the UK and the world that ensures accuracy and consistency of measurement. NPL ensures that cutting-edge measurement science and technology have a positive impact in the real world. NPL delivers world-leading measurement solutions that are critical to commercial research and development, and support business success across the UK and the globe.

Good measurement improves productivity and quality; it underpins consumer confidence and trade and is vital to innovation. We undertake research and share our expertise with government, business and society to help enhance economic performance and the quality of life. NPL's measurements help to save lives, protect the environment, enable citizens to feel safe and secure, as well as supporting international trade and companies to innovation. Support in areas such as the development of advanced medical treatments and environmental monitoring helps secure a better quality of life for all.

The Simpleware product group at Synopsys develops world-leading software solutions for the conversion of 3D image data (MRI, CT, X-ray CT, FIB-SEM...) into high quality design, simulation and 3D printing models. Use Simpleware to visualise, analyse, quantify and process your data, and to export surface models/meshes.

Simpleware is easy-to-learn and use, and includes video recording features and options to export surface models/meshes from segmented data for CAD and 3D printing. Additional modules are available for exporting CAE meshes, integrating image data and CAD, exporting NURBS and calculating effective material properties from scans.

The software is used for a variety of applications in the Life Sciences, Materials Sciences, and Industrial Reverse Engineering and Non-Destructive Testing fields. Simpleware software is ideal for visualising and analysing X-ray CT scans, enabling inspection of internal features, measurements and statistics generation, and export to FE/CFD solvers for simulating physical properties.

WMG at the University of Warwick is renowned for both collaborative research and development with global companies, and world leading, industry relevant education.

We work with companies from the automotive, aerospace and defence, business, construction, energy, healthcare, IT, security and rail sectors to push the boundaries of technology and develop products and processes that will have real impact on the economy and society.

By bringing together professors, researchers, engineers, and scientists from different fields, we encourage the transfer of knowledge into new applications, and a real entrepreneurial spirit. The results of that research work feed into our education programmes, and our students learn from the best.

ZEISS Extend the Limits of Exploration
ZEISS Xradia Versa 3D X-ray microscopes unlock new degrees of flexibility for scientific discovery. Building on industry-best resolution and contrast, Xradia Versa instruments expand the boundaries of non-destructive imaging for breakthrough flexibility and discernment critical to your research. Innovative contrast and acquisition techniques free you to seek-and find-what you've never seen before, to move beyond exploration and achieve discovery.

# Organising Committee

## Conference Chairs

Dr Wenjuan Sun ........................................................................NPL
Dr Alex Attridge ........................................................................WMG, University of Warwick

## Conference Co-chairs

Dr Jay Warnett ........................................................................WMG, University of Warwick
Mr Stephen Brown ........................................................................NPL

## Committee Members

Dr Farah Ahmed ........................................................................Natural History Museum
Dr Paul Bills ........................................................................University of Huddersfield
Prof Richard Leach ........................................................................University of Nottingham
Prof Michael McCarthy ........................................................................BSI
Prof Ian Sinclair ........................................................................University of Southampton
Mr Adam Thompson ........................................................................University of Nottingham
Dr Martin Turner ........................................................................University of Manchester
Prof Mark Williams ........................................................................WMG, University of Warwick