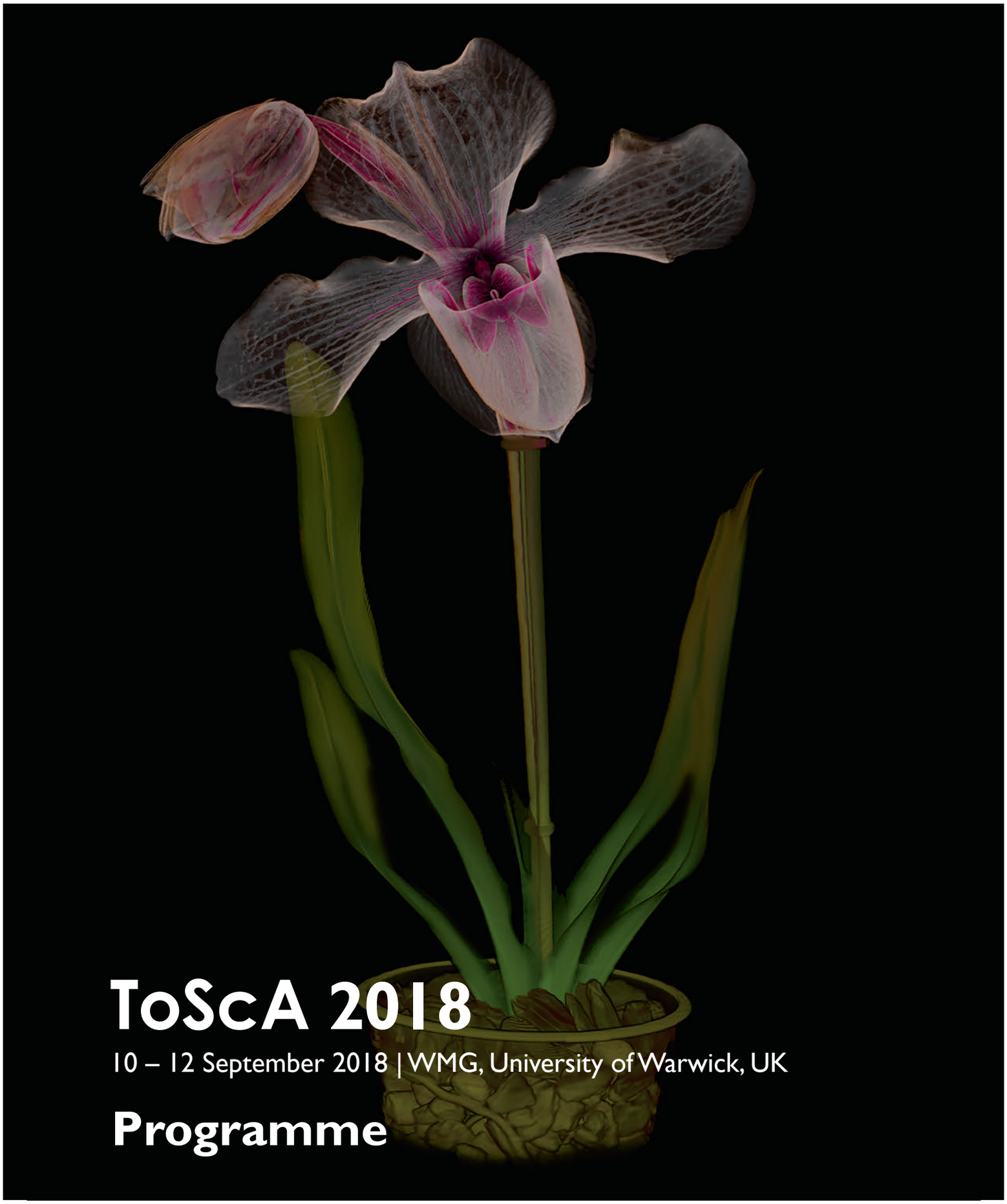

ToScA 2018

10 – 12 September 2018 | WMG, University of Warwick, UK

Programme

ToSCA
Tomography for Scientific Advancement

WMG
THE UNIVERSITY OF WARWICK

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Welcome

Symposium Chair: Dr Farah Ahmed (Natural History Museum, UK)

A warm welcome to the 6th annual meeting addressing the forefront of tomography related advances. This year's meeting presents innovation in research, practical applications in industry and demonstrates international collaborations at their best. ToScA 2018 covers a broad range of topics including, correlative imaging, bioengineering, manufacturing, data quantification and medical forensics. This international meeting consists of keynote speakers, student talks, student poster presentations and an image competition. The meeting provides opportunities for open discussions, networking with researchers and commercial industry as well as a platform to engage in collaborations.
I would like you to join me in thanking WMG, Dr Jay Warnett and Professor Mark Williams for hosting this year's meeting. The banquet dinner is being held at Warwick Castle, as usual I look extremely forward to an evening of eventful conversations!

Symposium Co-Chairs: Dr Jay Warnett & Professor Mark Williams (WMG, University of Warwick)

We are delighted to welcome this year's ToScA delegates to the University of Warwick. The University itself is only a little over 50 years old, having been founded just two years before the first commercial X-ray CT scanner! Despite its relative youth it has grown to be world-leading as a research intensive University with the highest academic standards. WMG (formerly Warwick Manufacturing Group) itself was founded in 1980's to support the reinvigoration of UK manufacturing through research and knowledge transfer and is the foundation of our research using the technique. From automotive development with nearby JLR to cultural heritage partnerships as far reaching as Oman, we are continually applying X-ray CT in diverse contexts and look forward to hearing how our colleagues in the community are creating similar innovation throughout the conference.

ToScA Committee

Farah Ahmed (Exponent), Chair
Graham Davis (QMUL)
Richard Johnston (Swansea University), Media Secretary
Gianluca Tozzi (University of Portsmouth), Treasurer
Jay Warnett (WMG, University of Warwick), Secretary

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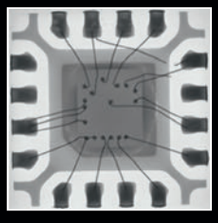

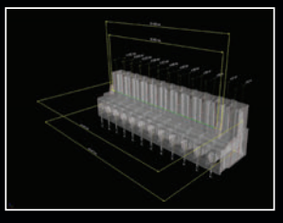

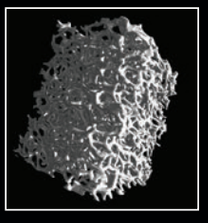

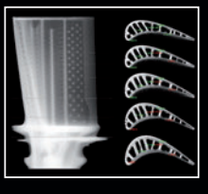

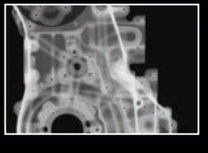

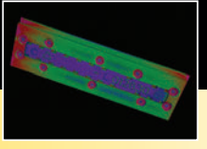

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Workshop Programme Monday 10 September 2018

Registration for those who have booked to attend workshops will take place at 09:00 at the IMC building. The morning workshop sessions will start at 09:30 and the afternoon sessions will start at 13:30. A light lunch will be provided.

Confirmed workshops include:

VGSTUDIO MAX Introductory Workshop (morning session)

This workshop will introduce you to CT data analysis and visualization using VGSTUDIO MAX. Volume Graphics will present typical workflows which are of special interest for the scientific community for the fast and precise analysis of voxel data: you will accomplish the first steps of quantitative analysis options, segmentation, and visualization techniques. Use VGSTUDIO MAX to easily get the information contained in your data sets, whether acquired by laboratory X-ray CT, a synchrotron, with neutrons, or with another source. Use this special opportunity to speak personally with Volume Graphics experts!

VGSTUDIO MAX Segmentation & Analysis Workshop (afternoon session)

This workshop will cover image segmentation and selected analyses available in VGSTUDIO MAX. Participants should be familiar with the basic operations of the software or have attended the VGSTUDIO MAX Introductory Workshop the same day. Volume Graphics will present typical segmentation tasks and solutions and give you tips and tricks for challenging multimaterial datasets. The second part of the workshop will be dedicated to selected quantitative analysis options. Take the chance to speak personally with Volume Graphics experts!

Amira-Avizo Software - Introductory Workshop (morning session)

This workshop is an introductory course focusing on the advanced 3D visualization and analysis capabilities of Amira and Avizo software for exploring and understanding scientific and industrial CT data. Participants will be offered an overview to data visualization, image processing and segmentation, measurements and statistics, and other advanced set of functionalities.
Attendees will have the opportunity to use the software through a hands-on session, accessible to first-time users of Amira and Avizo.

Amira-Avizo Software - Automation of Analysis Workflows Workshop (afternoon session)

Participants will be offered the chance to try some of the latest features of Amira and Avizo Software.
Amira and Avizo Software are well known software platforms for visualizing, inspecting, measuring and analyzing scientific and industrial CT data.
All the powerful features provided by Amira and Avizo Software can be customized and automated to perfectly fit with your research needs and to increase your productivity.
The workshop will focus on automation of analysis workflows in Amira and Avizo Software using for instance Python as well as recipe mechanism.

Laser Scanning Workshop (morning and afternoon session)

This workshop will be run twice, a session in the morning and then repeated in the afternoon.
This hands-on workshop will provide participants a basic working knowledge of 3D laser scanning using a manual measurement arm. An introduction to how the technology works, advantages and limitations will be given – particularly in a measurement/accuracy context. This will be followed by small group projects using a manual measurement arm to capture 3D data of an object and convert it to a usable mesh format for 3D printing or importing into other software. Registration of multiple scans and other more advanced techniques will be discussed/demonstrated with an opportunity to implement if time allows.

Invited Speakers

Dr Paul Bills, University of Huddersfield

Paul is the director of Graduate Education within the School of Computing and Engineering at the University of Huddersfield and is a key member and co-investigator in the EPSRC Future Metrology Hub with responsibility as research lead in area of metrology for medical and biological applications as head of the Bio-Metrology Research Group. This remit bridges aspects of implant technology to characterisation of bio-active films and biological structures and Paul has several doctoral students and funded projects within this area with a large number of external collaborating organisations. Paul was also a key member of the EPSRC Centre for Innovative Manufacturing in Advanced Metrology from 2011-2017, a role in which he developed a reputation as a world renowned expert on the subject of orthopaedic wear measurement.

Mr Barnaby Churchill Steel, Marshmallow Laser Feast

Barnaby Churchill Steel is a visual artist whose work bridges experimental genres and unfamiliar mediums, forging artistry, science and technology to sculpt the malleable texture of perception. He founded the creative studio 'Marshmallow Laser Feast' (MLF) with Robin McNicholas and Memo Akten back in 2010. MLF's glittering hoard of sensory nuggets includes music videos for U2; light painting machines for McLaren; and 'In The Eyes Of The Animal', which won the Audi Innovation Award. Most recently, he and the team at MLF won the Tribeca Film Festival Storyscapes Award for Innovation in Storytelling for 'Tree Hugger, Wawona'. Exploring the potential of new technologies to expand the senses and deepen our connection to reality.

Dr Maria Harkiolaki, Diamond Light Source

Maria is the acting Principle Beamline Scientist for beamline B24. Previously she was a group leader at the Structural biology laboratory at the Nuffield department of Medicine of the University of Oxford. Maria undertook her graduate studies at YSBL, York, and was awarded her PhD in 2002.

Professor Richard Leach, University of Nottingham

Richard is currently a professor in metrology at the University of Nottingham and prior to this spent 25 years at the National Physical Laboratory. Richard's research is dominated by what he calls "information-rich metrology": the enhancement of manufacturing metrology through the use of a priori information, often utilising concepts from artificial intelligence. His current interests are the dimensional measurement of precision and additive manufactured structures. Richard is on the Council of the European Society of Precision Engineering and Nanotechnology, the International Committee on Measurements and Instrumentation and several international standards committees. He is the European Editor-in-Chief for Precision Engineering. He has over 360 publications including five textbooks. He is a Fellow of the Institute of Physics, the Institution of Engineering & Technology, the International Society of Nanomanufacturing, the Institute of Measurement and Control and a Sustaining Member of the American Society of Precision Engineering. He is a visiting professor at Loughborough University and the Harbin Institute of Technology.

Professor Peter Lee, University College London

Peter is Professor of Materials Science in the Department of Mechanical Engineering, with his group part based at the Research Complex at Harwell, where he is Assistant Director, Physical Sciences. His research focusses on the computational simulation and x-ray imaging of materials at a microstructural level. He is the primary author of the open-source software, uMatIC, which simulates three phase flow to predict solidification microstructures. Peter is also an avid experimentalist, developing nano-precision rigs that simulate the processing of materials on a synchrotron beamline, enabling us to see inside materials in 3D as they change in time (termed 4D imaging). His work is revealing how microstructures evolve in aerospace and automotive materials, as well as biological and geological systems. His results and open-source codes have been exploited internationally by aerospace, automotive, energy and biomedical companies to solve important engineering challenges – from developing additive manufactured human joint replacements to light weight automotive components.

Dr Jeremy Opperer, Exponent International

Dr. Opperer has extensive experience in product hazard and risk assessment which he has gained while helping a variety of brands representing the consumer products, food and beverage, pharmaceutical, and baby products sectors. For more than 14 years, he has applied his knowledge of engineering design, manufacturing, and quality control process to help his clients to develop, manufacture, and distribute safe and quality products in the consumer goods market. He supports his clients in three main areas: proactive assessment, reactive incident investigations, and by reviewing and improving the "concept to consumer" product development process. He has a strong focus on the "consumer experience" and the human factor of product interaction.

Professor Mark Williams, University of Warwick

Mark is a Professor at WMG and leader of the Product Evaluation Technology research group and head of the Centre for imaging, Metrology, and Additive Technology (CiMAT). His role involves the delivery of Metrology, Additive Manufacturing and Visualisation research projects within Automotive, Aerospace, Medical and Law Enforcement sectors. Recent expansion of research interests into Industrial and Criminal Forensics has seen his group provide evidence in over 80 Homicide cases for Police Forces across the country resulting in an individual Chief Constable Award and IET Outstanding Achievement medal in 2016. Mark is also a Chartered Engineer and Fellow of the IMechE.

Programme

Tuesday 11 September

08.45 – 09.30	Registration, Tea and Coffee
09.30 – 09.45	Welcome and Introduction ***Farah Ahmed, Exponent & Jay Warnett, University of Warwick***

Session One: Correlative CT (*Session Chair: Richard Johnston)*

09.45 – 10.15	**Keynote Talk:** Correlative soft-X ray cryo-tomography and super resolution fluorescence microscopy imaging for the life sciences at Diamond Light Source beamline B24 ***Maria Harkiolaki, Diamond Light Source***
10.15 – 10.30	Multi-scale and multi-modal investigations of the acorn barnacle (Semibalanus balanoides): an example of correlative imaging and bio-inspiration ***Ria Mitchell, Swansea University***
10.30 – 10.45	Correlative X-ray and neutron tomography of root systems using cadmium fiducial markers ***Thomas Clark, University of Southampton***
10.45 – 11.00	Correlative micro-computed tomography & serial block-face scanning electron microscopy of heavy metal-stained bone tissue allows 3D imaging of the osteocyte network ***Patricia Goggin, University of Southampton***
11.00 – 11.30	Tea, Coffee and Exhibition, Posters and Image Competition

Session Two: Quantification (*Session Chair: Nick Brierley)*

11.30 – 12.00	**Keynote Talk:** Traceability in industrial X-ray computed tomography: the story so far ***Richard Leach, University of Nottingham***
12.00 – 12.30	**Keynote Talk:** Advances in Cone-Beam Scatter Reduction ***Chris Price, Nikon Metrology***
12.30 – 12.45	A versatile approach to x-ray micro-tomography with adjustable contrast-to-noise ratio and spatial resolution ***Charlotte Hagen, University College London***
12.45 – 13.00	Strain uncertainties on magnesium scaffolds for bone regeneration using digital volume correlation ***Roxane Bonithon, University of Portsmouth***
13.00 – 13.15	AGM
13.15 – 14.15	Lunch and Exhibition, Posters and Image Competition

Session Three: Manufacturing and Industry Applications *(Session Chair: Martin Turner)*

14.15 – 14.45	**Keynote Talk:** Practical Applications of CT for Product Failure Analysis ***Jeremy Opperer, Exponent International***
14.45 – 15.00	Three-dimensional damage morphologies of thermomechanically deformed sintered nano-silver die attachments for power electronics modules ***Pearl Agyakwa, University of Nottingham***
15.00 – 15.15	Combined use of µCT, IR Thermography and FIB-SEM systems for multi-modal and multi-resolution manufacturing quality control ***Grzegorz Pyka, Thermo Fisher Scientific***
15.15 – 15.30	Image-Based Control and Characterization of Lithium-Ion Batteries and Materials ***Rémi Blanc, Thermo Fisher Scientific***
15.30 – 16.00	Tea, Coffee and Exhibition, Posters & Image Competition

Session Four: Medical and Forensics (*Session Chair: Graham Davis)*

16.00 – 16.30	**Keynote Talk:** How Engineers helped solve the body in a suitcase ***Mark Williams, University of Warwick***
16.30 – 16.45	Morphological substrates for atrial arrhythmogenesis in a congenitally malformed heart with atrioventricular septal defect ***Robert Stephenson, Aarhus University Hospital***
16.45 – 17.00	Colonic cycloramas for the study of the early stages of colorectal cancer: advanced image visualisation for synchrotron-based X-ray phase contrast computed tomographic data ***Charalambos Rossides***, ***University of Southampton***
17.00 – 17.15	High-resolution x-ray tomographic characterization of hierarchical multiscale nanofibrous scaffolds for tendon tissue regeneration ***Alberto Sensini, University of Bologna***
17.15 – 18.00	Lightning Talks
18.15	Symposium Banquet at Warwick Castle

Wednesday 12 September

Session Five: Bioengineering and Life Sciences *(Session Chair: Gianluca Tozzi)*

09.00 – 09.30	**Keynote Talk:** Metrology of Biofilms in Extreme Environments ***Paul Bills, University of Huddersfield***
09.30 – 10.00	**Keynote Talk:** None-destructive imaging of biological structure in 3D ***John Flynn, Carl Zeiss Microscopy***
10.00 – 10.15	Biophysical comparison of the outer ear in bush-crickets (Orthoptera: Tettigoniidae): pressure or gradient difference receiver? ***Sarah Aldridge, University of Lincoln***
10.15 – 10.30	Mapping 3D Networks in Human Lung Tissue using Micro-Computed Tomography and Immunofluorescence ***Matthew Lawson, University of Southampton***
10.30 – 10.45	3D X-ray histology by means of micro-computed tomography: A streamline workflow for high-resolution 3D imaging of biopsy specimens ***Orestis Katsamenis, University of Southampton***
10.45 – 11.15	Tea, Coffee and Exhibition, Posters & Image Competition

Session Six: Understanding Materials *(Session Chair: Philipp Schneider)*

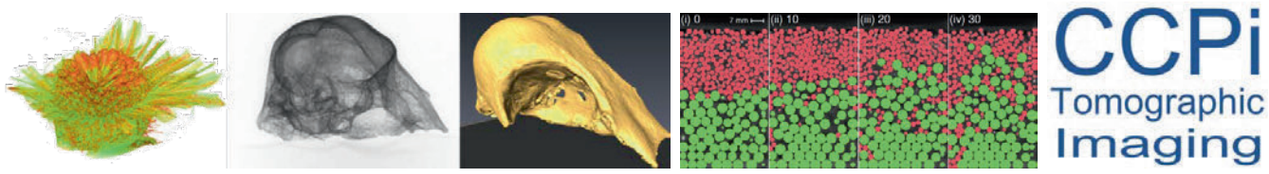
11.15 – 11.45	**Keynote Talk:** In situ and operando synchrotron tomographic characterisation of semi-solid processing ***Peter Lee, University College London***
11.45 – 12.00	Multiscale correlative characterization of environmentally assisted crack initiation, propagation and failure in a high strength aa5083 h131 alloy ***Visweswara Gudla, University of Manchester***
12.00 – 12.15	Application of XCT to Steelmaking – Building up the Big Picture ***Stephen Spooner, University of Warwick***
12.15 – 12.30	Understanding materials evolution using dynamic X-ray imaging in the laboratory ***Arno Merkle, TESCAN XRE***
12.30 – 13.30	Lunch and Exhibition, Posters and Image Competition

Session Seven: Acquisition techniques *(Session Chair: TBC)*

13.30 – 14.00	**Keynote Talk:** Advanced image acquisition and analysis; combining HeliScan microCT and Avizo Software ***Grzegorz Pyka, Rémi Blanc, Thermo Fisher Scientific***
14.00 – 14.15	Enabling temporal CT in the lab through reprogramming existing machines ***Jakob Jorgensen, University of Manchester***
14.15 – 14.30	Complementary non-destructive analytical techniques for materials science application: neutron and X-ray imaging ***Genoveva Burca, STFC-Rutherford Appleton Laboratory***
14.30 – 14.45	4D Laboratory X-ray microscopy for the in-situ investigation of drug release in a push-pull osmotic pump tablet ***Stephen Kelly, Carl Zeiss X-ray Microscopy***
14.45 – 15.00	Full-Field Strain Analysis of Newly Formed Bone Induced By BMP-2 Loaded Hydrogels ***Marta Peña Fernández, University of Portsmouth***
15.00 – 15.30	Tea, Coffee and Exhibition, Posters & Image Competition

Session Eight: Cultural Heritage (*Session Chair: Daniel O'Flynn)*

15.30 – 16.00	**Keynote Talk:** Experiencing the world beyond our senses ***Barnaby Churchill Steel, Marshmallow Laser Feast***
16.00 – 16.15	The Oxford Dodo: a cold case ***Jay Warnett, University of Warwick***
16.15 – 16.30	Micro CT of large fossils at the ESRF European Synchrotron : The case of mammal forerunner burrow casts ***Vincent Fernandez, Natural History Museum***
16.30 – 16.45	Understanding Blind and Partially Sighted (BPS) perception of Natural History Objects for 3D Printing Applications ***Paul Wilson, University of Warwick***
16.45 – 17.15	Panel Discussion and Final Remarks



Collaborative Computational Project in Tomographic Imaging: www.ccpi.ac.uk

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Core CCPi provides the community with a toolbox of algorithms increasing the quality and level of information that can be extracted by computed tomography. Chaired by Prof Philip Withers (University of Manchester) and co-ordinated by staff within the Science and Technology Facilities Council it is led by a working group of experimental and theoretical academics with links to the Diamond Light Source, ISIS Neutron Spallation Source and Industry.

- **Creating and supporting frameworks from the national facilities to lab based systems.**
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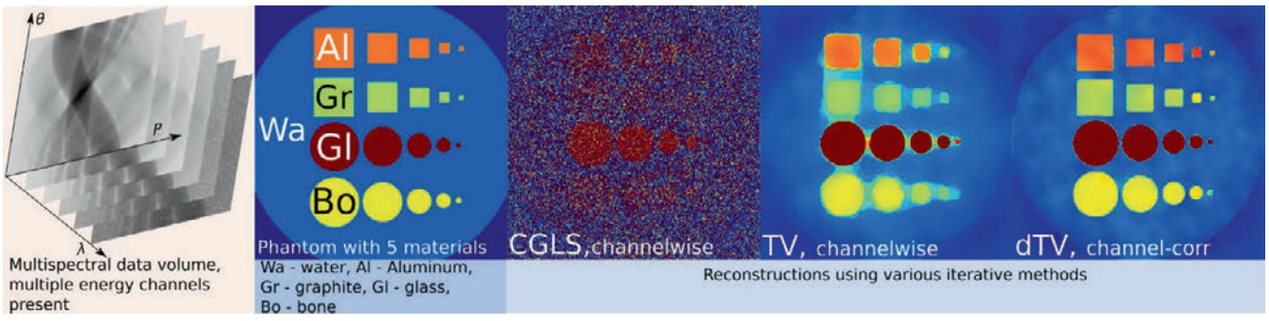
CCPi Flagship: Reconstruction Toolkit for Multichannel CT Conventional computed tomographic imaging is stuck in a black and white (single channel) era. Technological breakthroughs in energy-sensitive detectors and time-of-flight methods enable a new era of tomographic imaging in 'colours' (multiple channels) – leading to chemical tomography extracting materials linked to their unique k-edge signatures.



Credit: E. Pasca, S. Nagella, R. Fowler, M. Turner, B. Searle (STFC), R. Atwood (DLS), T. Lowe, R Garwood, D. Kazantsev, J. Jørgensen P. Gajjar [Rev of Sci. Inst.,2018] (Manchester)

EPSRC Engineering and Physical Sciences Research Council

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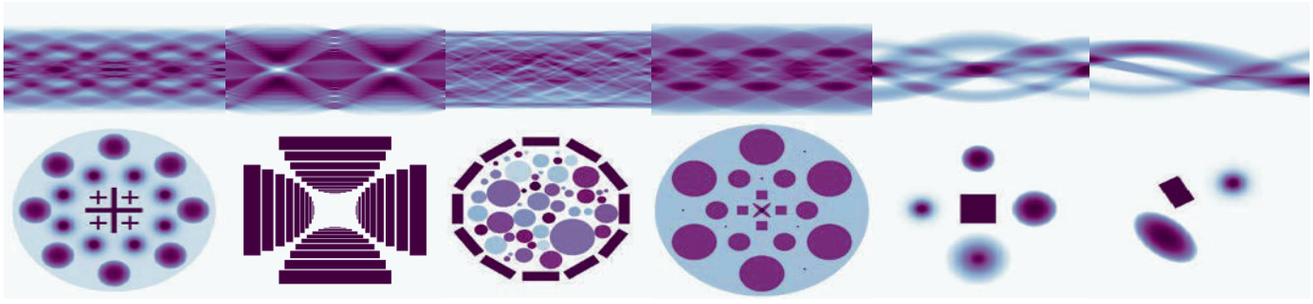
CoSeC Computational Science Centre for Research Communities

Science & Technology Facilities Council



Oral Abstracts

Session 1: Correlative CT

Correlative Soft-X Ray Cryo-Tomography and Super Resolution Fluorescence Microscopy Imaging for the Life Sciences at Diamond Light Source Beamline B24

Maria Harkiolaki

Diamond Light Source

B24 is the full field X-ray tomography beamline at Diamond currently delivering X-ray absorption contrast imaging of biological material (cells and tissue sections) to a resolution of 40nm. The resulting cryo Soft X-ray Tomography (cryoSXT) 3D data allows the unambiguous delineation of cellular ultrastructure and is employed in the interpretation of the effects of biological chemical and mechanical cues depending on the subject matter. The B24 soft X-ray microscope is currently fully operational and available to the wider user community.
CryoSXT also provides context for further investigation on the molecular level. The latter is gained via super resolution fluorescence microscopy methods that provide invaluable information as to the molecular localisation of key parameters relevant to the system under study within the context of cellular maps defined via cryoSXT. To that effect, at B24, a bespoke cryo fluorescence super resolution microscope has been developed offering both cryo-Structured Illumination Microscopy (cryoSIM) and dSTORM. The particular attraction of the system is that samples due to be used for X-ray imaging can be processed there first to generate 3D fluorescence information at high resolution on identified areas of interest before taken to the transmission X-ray microscope. This allows the accumulation of directly correlated localisation data (the same sample is imaged through a variety of methods) eliminating sample to sample variations and allowing the unambiguous interpretation of data across modalities. The B24 cryoSIM capacity is at present fully implemented and is available to the user community on a commissioning basis. dSTORM is implemented optically but has not been tested with samples yet. Software is being developed to handle data processing and correlation across imaging modes.
The beamline workflow will be presented with examples of recent data collected along with highlights and pitfalls of the correlative scheme employed on site.

Multi-Scale and Multi-Modal Investigations of the Acorn Barnacle (*Semibalanus Balanoides*): An Example of Correlative Imaging and Bio-Inspiration

Ria L. Mitchell[1], Peter Davies[1], Mark P. Coleman[1], Cameron Pleydell-Pearce[1], Laura North[1], Will Harris[2], and Richard E. Johnston[1]

[1.] Advanced Imaging of Materials (AIM) Facility, College of Engineering, Swansea University, Swansea, UK
[2.] Carl Zeiss X-ray Microscopy, Pleasanton, CA, USA

***Keywords**: Correlative imaging, FIB-SEM, Multi-modal, Multi-scale, Barnacle, Bioinspiration*

Natural-forming biomaterials, particularly in the marine realm, can be subject to extremes of moisture, loading, salinity, temperature, and predation. Through evolution and adaptation, organisms have developed an incredibly diverse range of strategies to survive despite these unpredictable conditions; this includes the development of complex chemical-biological-structural relationships, which not only enhance structural integrity but also maximize the resources available to them (e.g., composition of seawater for hard-part biomineralization).
This process of formation and function is better understood by investigating complex biological systems and their physical properties at various length-scales using correlative imaging. Correlative imaging is useful because it assesses how features at the centimetre to nanometre scale are connected (and vice-versa) by combining information from multiple modalities (e.g., physical-chemical-crystallographic-mechanical properties) and allowing us to identify and correlate regions of interest across dimensions (2D-3D-4D).
Here, the microstructural properties and crystallographic orientation of wall-plate joints (ala) in the barnacle *Semibalanus balanoides* were characterized and correlated at varying length-scales using optical light microscopy (LM), X-Ray micro CT (X-ray µCT) and focused ion beam milling (FIB) linked with scanning electron microscopy (SEM). The ala are the interlocks between neighboring plates and are often 'shared' between adjoining organisms; here, the organism can grow, whilst also attempting to remain structurally strong. Targeted region of interest µCT scans reveal complex interactions and relationships between neighboring plates that can only be identified via non-destructive 3D methods; in addition, complex ala pore networks have been identified for the first time. OM, SEM and EBSD indicate specific crystallographic orientations at the ala tips, which has implications for

natural strengthening and preferred oriented biomineralisation. Further, FIB milling and imaging sheds light on nano-pore networks in the ala tip. Understanding these features not only contributes towards general understanding of the biomineralization process in barnacles, but also how barnacles may be considered for bio-inspiration of human-made materials and structures. The work demonstrates that correlative methods spanning different length-scales, dimensions and systems enable the extension of biological understanding.

Correlative X-Ray and Neutron Tomography of Root Systems using Cadmium Fiducial Markers

Thomas Clark[1], Dr Genoveva Burca[2], Dr Richard Boardman[1], Dr Samuel Keyes[1], Prof. Ian Sinclair[1], Dr Thomas Blumensath[1]

[1]University of Southampton, UK
[2]STFC, Rutherford Appleton Laboratory, ISIS Facility, Harwell, UK

Keywords: *X-ray, Neutron, Tomography, Image registration, Cadmium, Fiducial markers, Plant roots, Soil, Rhizosphere*

The interactions between plant roots and soil are an area of active research, particularly in terms of water and nutrient uptake. Since non-invasive *in vivo* studies are required, tomographic imaging appears an obvious method to use, but no one imaging modality is well suited to capture the complete system. X-ray imaging gives clear insight to soil structure and composition, however water is comparatively transparent to X-rays and biological matter also shows poor contrast. Neutron imaging presents a complementary view where water and biological matter are better distinguished but the soil minerals are not imaged as clearly as they would be with X-rays.
This work aims to develop robust methods for complementary X-ray/neutron tomographic imaging of plant root samples which should lead to new insight into water transport in soil. One of the key challenges is to register a pair of reconstructed volume images of a sample that will typically have been produced with entirely separate facilities.
One approach to this challenge that has been investigated is through the use of fiducial markers for point-based registration. Since X-rays and neutrons are attenuated differently a material must be chosen that will provide adequate contrast in both modalities to allow easy segmentation of the fiducial markers. In this case cadmium was selected as a suitable candidate.
Simulations were conducted to investigate the expected registration accuracy as the quantity and distribution of the markers varied. The findings of these simulations were then tested experimentally as plant samples were grown and imaged using neutrons with the IMAT instrument at ISIS Neutron and Muon Source and with X-rays at µ-VIS X-ray Imaging Centre at the University of Southampton.
These results show the accuracy of the registration in comparison to predictions from simulations and display the potential of correlative X-ray/neutron CT for examining plant roots and soil.

Correlative Micro-Computed Tomography & Serial Block-Face Scanning Electron Microscopy of Heavy Metal-Stained Bone Tissue Allows 3D Imaging of the Osteocyte Network

Patricia Goggin[1], Richard O.C. Oreffo[2], Philipp Schneider[1]

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MOTIVATION: Osteocytes form a network within mineralised bone, pivotal for bone health. To characterise the osteocyte network, including processes and to better understand its role for diseases such as osteoporosis, high-resolution 3D imaging of osteocytes and their surrounding matrix across multiple length scales is necessary (1). Therefore, we developed a correlative approach based on X-ray computed tomography (µCT) and serial block-face scanning electron microscopy (SBF SEM). µCT is an established technique that maps thousands of osteocyte lacunae at resolutions around and below 1 µm (2). However, it relies on contrast provided by the mineralised bone, showing osteocyte lacunae indirectly as porosity of the matrix, while the osteocytes remain invisible. SBF SEM is a high-resolution (<100 nm) 3D technique (3) in which resin-embedded tissue is automatically imaged and sliced, providing 3D data of both the matrix and cellular elements (1). We present a

protocol using heavy metal staining and a correlative µCT & SBF SEM approach, which allows concurrent imaging of the bone matrix and osteocytes including processes across length scales.
METHODS: Bone tissue from the murine tibiofibular junction (~2 mm3) was fixed, decalcified, processed using heavy metals, then dehydrated and resin embedded (4). Blocks were scanned using µCT (Zeiss/Xradia Versa 510) at a voxel size of 1.5 µm. The block was further trimmed and imaged using a Gatan 3ViewXP2 system in a Quanta 250 FEGSEM. The osteocyte network (and the vasculature) was subsequently segmented and visualised using ImageJ (5) and Avizo software.

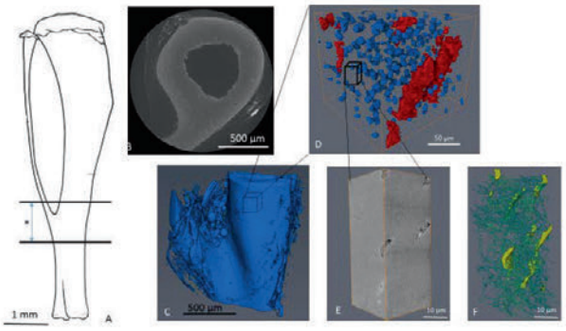

*Figure 1: (A) Mouse tibiofibular junction *. (B) µCT data of heavy metal-stained bone tissue. (C) Volume reconstruction of µCT data. (D) Osteocytes and intracortical vascualture segmented from B. (E) Subvolume imaged using SBF SEM. (F) Segmented data from E showing osteocytes (yellow) and their cell processes (green).*

RESULTS: Correlative high-resolution µCT & SBF SEM of heavy-metal bone tissue facilitated direct imaging of the osteocyte network in its native 3D context, including osteocytes and their cell processes (Figure 1).
DISCUSSION: µCT scanning of bone, decalcified and stained for electron microscopy enables direct imaging of osteocytes, vasculature and surrounding bone matrix. It covers the osteocytes of relatively large bone volumes and permits selection of volumes of interest for high-resolution SBF SEM showing osteocytes and their cell processes, which are beyond the reach of µCT (~100 nm). Our correlative approach provides 3D data for quantitative morphological analysis of osteocytes in health and disease and for image-based computational approaches in bone mechanobiology.

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[1] PM Goggin, KC Zygalakis, RO Oreffo, P Schneider (2016). European Cells and Materials 31:264-95
[2] P Schneider, M Stauber, R Voide, et al. (2007). J Bone Miner Res 22:1557-70
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Session 2: Quantification

Traceability in Industrial X-Ray Computed Tomography: The Story so Far

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X-ray computed tomography (XCT) has a number of benefits over traditional contact and optical techniques for coordinate metrology; not least because it allows one to peer inside the object being measured. But how do we know we are getting the right answers? As yet, there is no commonly-adopted performance verification or calibration infrastructure in place for XCT, so the sceptic's (i.e. most metrologists') answer to the question is: we don't. Specification standards for performance verification are being drafted in ISO 213, which make an attempt to map onto the standards developed for contact and optical methods, but is this really the most effective way to go? To achieve traceable measurements with contact coordinate measuring systems, complex kinematic models of the system are combined with Monte-Carlo simulations to estimate measurement uncertainties for a given object. There is as yet no equivalent for optical instruments, and XCT instruments are even further behind. Whilst there have been valiant attempts to produce such so-called "virtual instruments" for XCT, the complex physics of X-ray-matter interactions means that there is still a long way to go. Meanwhile, in the surface topography measuring world, there is a calibration framework being standardised that relies on so-called "metrological characteristics" that are designed to quantify the various influence factors that affect the

uncertainty in a measurement carried out with a surface topography instrument. These characteristics include familiar concepts such as scale linearity and amplification coefficient for the height response of an instrument. Once in place, users determine the various metrological characteristics with a set of calibration artefacts, then use the resulting values along with an appropriate measurement model to estimate measurement uncertainty. This framework is not perfect – there are some technical issues that mean it only applies with a limited range of surface types, although there is on-going research to address the remaining issues. This talk will discuss the background to calibration in coordinate metrology and ask the question: can we define a calibration framework for XCT based on a defined set of metrological characteristics?

Advances in Cone-Beam Scatter Reduction

Chris Price

Nikon Metrology

When highly attenuating materials or objects with a long X-ray path length are imaged with X-ray CT, X-ray scatter artefacts degrade image quality, particularly at beam energies above 225kV. Scatter manifests itself as localised changes in X-ray attenuation (represented by greyvalues), degrading the image both visually and in terms of contrast-to-noise ratio (CNR). The traditional approach to reduce scatter is to collimate the cone beam, which constrains the X-rays into a horizontal plane (fan beam) and to employ the use of a linear detector with a collimated input window, which prevents scattered X-rays from outside of this plane being detected. This drastically reduces scatter, however the reconstructed data is in the form of 2D slices rather than a 3D volume resulting in decreased throughput.
We present a method of scatter reduction for 3D cone-beam CT using a beam-stop array consisting of a grid of tungsten pins. These pins attenuate virtually all incident X-rays, therefore any detector illumination in the corresponding grid of shadows consists only of scatter. The greyvalues from the shadow grid thus provide an image of scatter distribution across the detector. Based on this, we can selectively subtract two distinct sources of scatter: system scatter (including that originating from cabinet walls and within the detector itself) and object scatter (from the sample itself).
This method results in reconstructed images, which enables more accurate segmentation, but also have an improved CNR. Samples that could traditionally only be scanned slice-by-slice with a linear detector can now be imaged in full on an area detector with comparable quality.

A Versatile Approach to X-Ray Micro-Tomography with Adjustable Contrast-To-Noise Ratio and Spatial Resolution

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Keywords: *Micro-tomography, X-ray phase contrast, Specimen imaging*

X-ray micro-tomography has become increasingly important for the inspection of specimens in both materials science and biomedicine, due its ability to provide detailed images non-destructively, in 3D, and within short scan times. In general, the resolution and contrast-to-noise ratio (CNR) requirements of these applications are hard to predict in advance, or vary from specimen to specimen, implying that a flexible approach is needed with respect to these metrics. In standard micro-tomography systems, spatial resolution is usually defined by the source and detector characteristics, and although it can be tuned slightly by adjusting the setup geometry, it cannot exceed the smaller of the focal spot or pixel blur. CNR, which is typically based on x-ray attenuation, can only be improved by increasing the exposure time, unless exogenous contrast agents are used. Again, this does not leave much freedom for adjustment, as constraints on radiation dose and/or scan time are likely to prohibit exposing for longer.
This talk will discuss how the versatility of x-ray micro-tomography can be increased by structuring the beam into an array of physically separated beamlets by means of a mask. As the smallest feature size that can be detected is determined by the beamlet width, this effectively decouples spatial resolution from the source and pixel dimensions [1]. Structuring the beam also comes with a simple option of improving CNR without increasing the exposure time or utilising contrast agents: by positioning an array of beam stops in front of the detector, the setup is transformed into an "edge illumination" imaging device, providing access to phase contrast and thereby increasing its sensitivity [2].

This talk will provide an overview of the beamlet-based approach and demonstrate its versatility, with spatial resolution regimes ranging from hundreds to a few micrometres accessible, and > ten-fold CNR improvement for weakly attenuating specimens feasible.

References:
[1] Diemoz PC, Vittoria FA, Olivo A, "Spatial resolution of edge illumination x-ray phase contrast imaging", Optics Express 22, 15514-29, 2014
[2] Hagen CK, Diemoz PC, Olivo A, "On the relative performance of edge illumination x-ray phase contrast CT and conventional, attenuation-based CT", Medical Physics 44, 1876-85, 2017

Strain Uncertainties on Magnesium Scaffolds for Bone Regeneration Using Digital Volume Correlation

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Digital volume correlation (DVC) combined with high-resolution X-ray computed tomography (XCT) offers a powerful tool to measure full-field displacement and strain in scaffolds following mechanical testing. Several studies reported the importance of testing precision (SDER) and accuracy (MAER) of the DVC software before performing *in situ* mechanics [1]. Magnesium-based implants show very promising biological evidence as biodegradable material [2]. To further investigate its use as a bone defect treatment, its mechanical behaviour needs to be fully understood. The aim of this preliminary study is to measure DVC strain uncertainties and morphometric parameters for magnesium-based implants. Zero-strain repeated scans were performed on a magnesium cylindrical scaffold (D: 8mm x H: 7mm) using 3D X-ray microscope Zeiss Versa 510 and the reconstructions had a voxel size of 7.95 μm. Morphometric analysis was conducted using ImageJ® 1.52d and Avizo® 9.4.0 software and DVC using DaVis® 8.4.0 software. A volume of interest was cropped in the centre of the scaffold (600x600x720 voxels). Precision (SDER) and accuracy (MAER) for strain values were calculated using MatLab® R2017a software for 8 sub-volumes sizes ranging 16-128 voxels [3]. MAER ranged 33-9406 με and SDER 38-6533 με with smaller sub-volumes producing less accurate/precise DVC output in accordance with previous literature on bone [1]. The maximum accepted strain error, related to a magnesium scaffold with yield stress of 43 MPa and Young's modulus of 1.85 GPa is 232 με (*yield stress / Young's modulus*). Thus, acceptable MAER and SDER values ranging 33-362 με and 38-332 με, respectively, were found between sub-volume sizes of 64 and 80 voxels. These sub-volumes will be used to further investigate magnesium scaffold mechanical properties *in situ*. The magnesium-based scaffold presented a very high connectivity network with pore sizes resembling trabecular bone architecture [4] (Fig. 1) and suggesting the possibility to use such material as bone defect regeneration treatment.

References:
[1] Dall'Ara, E., et al., 2017. Frontiers in Materials 4 doi: 10.3389/fmats.2017.00031.
[2] Zhao, D., et al., 2016. Biomaterials 112, 287-302 doi: 10.1016/j.biomaterials.2016.10.017.
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[4] Gonzalez-Garcia, R., et al., 2012. Clinical Oral Implants Research 24, 871-879 doi: 10.1111/j.1600-0501.2011.02390.x.

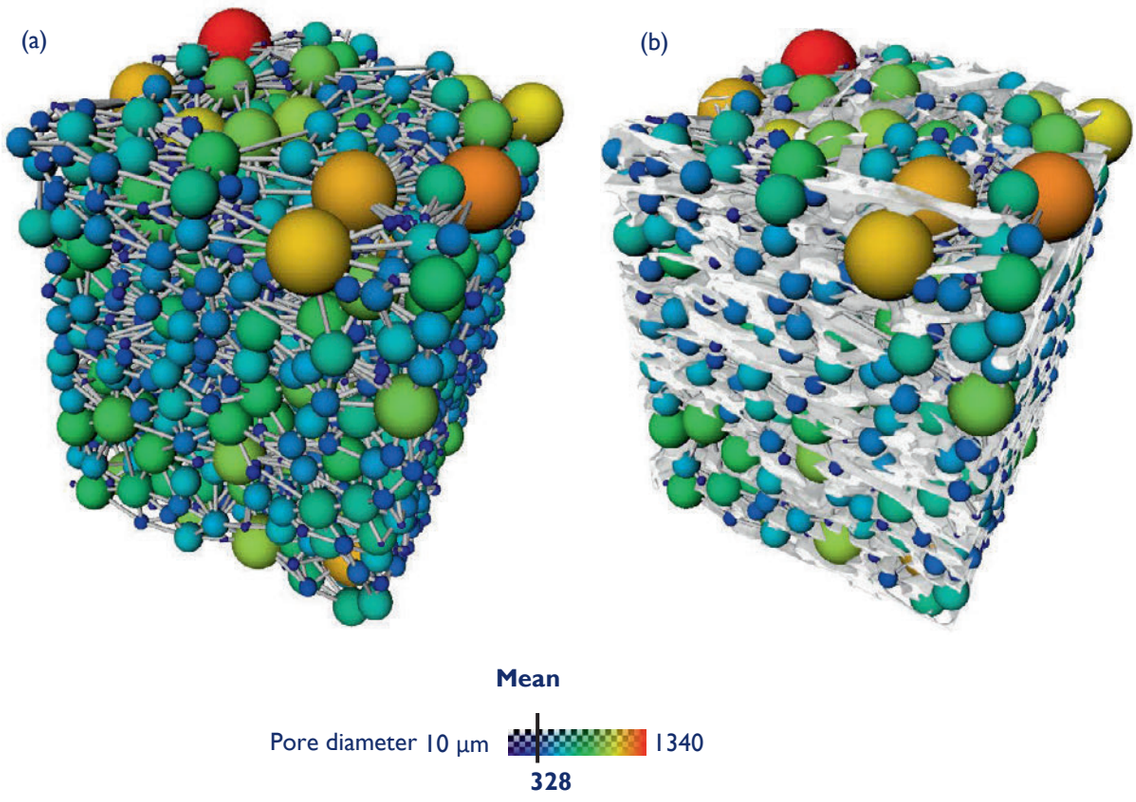

Figure 1: Mg-scaffold pore network (a) and its distribution (b) within the porous structure.

Session 3: Manufacturing and Industry Applications

Practical Applications of CT for Product Failure Analysis

Jeremy Opperer

Exponent International

Product failures can present themselves in a multitude of ways, ranging from events where the product looks pristine but lacks functionality to events where the product has undergone a catastrophic event such as an explosion. The product involved could be a relatively simple design comprised of only a handful of materials, to one with thousands of individual components constructed from a multitude of materials. Regardless of the product complexity or nature of the failure, sound product failure analysis begins with a thorough non-destructive assessment, and computed tomography is an essential tool for such assessments.
For this presentation, the practical use of CT will be presented through selected case studies which highlight how industry has used the technology to solve contemporary challenges. The visualization of a product as-received can help to paint the picture of what happened to the product and can provide clues to the events leading up to the product failure. This presentation addresses a range of practical applications used in the consumer products industry for electronic products, including battery inspections. We will discuss the type of information gathered using CT and how it is applied in the analysis, e.g., material density, geometry, and dimensional data.

Three-Dimensional Damage Morphologies of Thermomechanically Deformed Sintered Nano-Silver Die Attachments for Power Electronics Modules

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Keywords: *Sintered nano-silver, X-ray tomography, microstructure, thermomechanical fatigue, Reliability, power electronics*

Soldering is the most widely used die attachment method for power module packaging. However, conventional tin-based solder alloy die-attachments are inadequate for the emerging, more challenging wide band gap applications due to their susceptibility to thermomechanical fatigue and creep. Sintered nano-silver die attachments may be more suitable due to their superior electro-thermal properties and perceived reliability advantages. However, there is insufficient knowledge of their degradation mechanisms and reliability behaviour. In a recent comparative study [1], it was shown that the effective thermal resistance of a sintered nano-silver attachment barely changed after 100,000 power cycles (Fig. 1), in complete contrast to conventional solder alloy joints, whose thermal resistance rose sharply right from the outset and resulted in a lifetime at most a tenth of that of the sintered attachment. This paper investigates this remarkable relative stability under power cycling by considering damage morphologies and their influence on the thermal path. A chronological study of evolving thermomechanical fatigue damage has been undertaken, correlating data from 3D X-ray tomography with thermal impedance measurements. Lateral views of crack development are presented, which show networks of cracks analogous to those observed in the desiccation of soils (see Fig. 2). Segmentation and three-dimensional meshing using *AVIZO Fire* software are utilised to visualise the changing morphologies of specific micron-scaled defects. These provide compelling evidence for the hypothesis that shrinkage associated with continued heterogeneous densification of the sintered joint during thermal cycling plays a major role in driving the initiation and propagation of the cracks. Analysis of the texture (differing levels of x-ray absorption) of virtual cross-sectional images reveals a connection between crack patterns and non-uniformity of packing density due to depressions on the substrate. Finally, the aspect ratio and orientation of cracks within the sintered joint are shown to negligibly disrupt the conduction pathway of the joint.

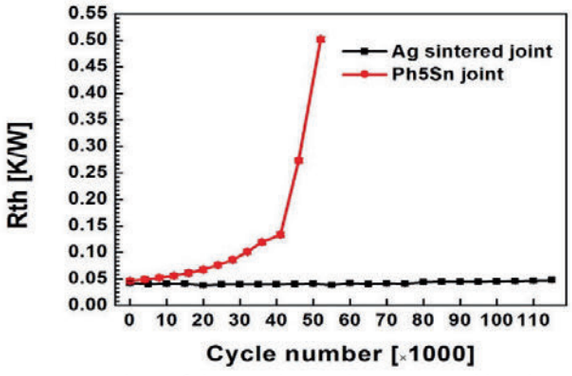

Figure 1. Sequential thermal resistance values of die attachment layers in a soldered specimen (a) and sintered sample (b) during a power cycling test.

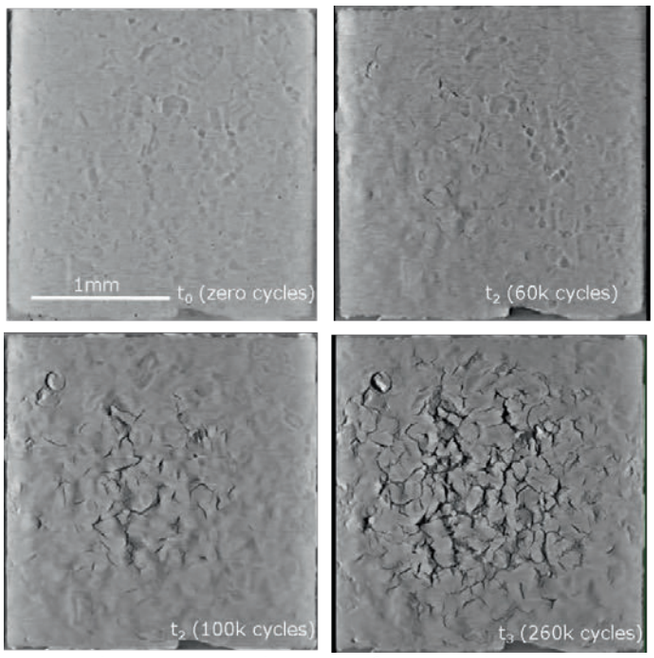

Figure 2. Virtual X-ray tomography cross-sectional images of a sintered Ag joint die attachment showing evolving microstructures under power cycling

References:
[1] J. Dai, J.F. Li, P. Agyakwa, M. Corfield and C.M. Johnson, IEEE TDMR DOI: 10.1109/TDMR.2018.2825386

Combined use of µct, IR Thermography and FIB-SEM Systems for Multi-Modal and Multi-Resolution Manufacturing Quality Control

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Keywords: *Defects analysis, Multi-scale imaging, Multi-modal imaging*

Due to the growing complexity of novel engineering materials, many require data collected from disparate imaging modalities with large differences in the precision and resolutions. This variation creates challenges in the process optimization steps that allow a smooth sample transition between various tools, but also in the direct cross-link correlation between the achieved results.
In this study we demonstrate a potential approach for precise defects detection/analysis which involves the combined use of µCT and ELITE Systems, and linking the workflow to FIB/SEM by taking advantage of the correlative toolkit.
The procedure is applied to the investigation of a large (120x220mm) PCB board and the embedded electronic devices. As a first step the tested sample is investigated with multi-scale µCT based investigation: full sample volume scan followed by multiple ROIs imaging. The multiple ROI imaging approach allows for a reduction by half, of the achievable voxel size, in comparison to standard full sample scans, while still maintaining total object volume data. This procedure allows the investigation of the printed Cu layers, as well as to detect potential defects in the electronic components and/or their connectivity within the board.
Individual components identified as potentially damaged, are further examined with the ELITE System, followed by the 3D high resolution uCT imaging. IR Thermography technology applied in the ELITE System allows pre-defining the location of faulty sections within semiconductor samples with a precision down to 50um across the sample surface measurement area. However, limited information is provided about both the depth position of

the defect with respect to the sample thickness, and defect type. Therefore, the use of high resolution uCT imaging of the faulty sample volume provides this missing information.
In such a way, using the ELITE system in combination with the large volume scanning capabilities of the uCT system allows for more precise damage location and preliminary identification of the defect type. Additionally, generated high resolution 3D uCT data allows for direct targeting of the individual defect with FIB/SEM via the correlative workflow approach, avoiding potential manual sample preparation and damage.

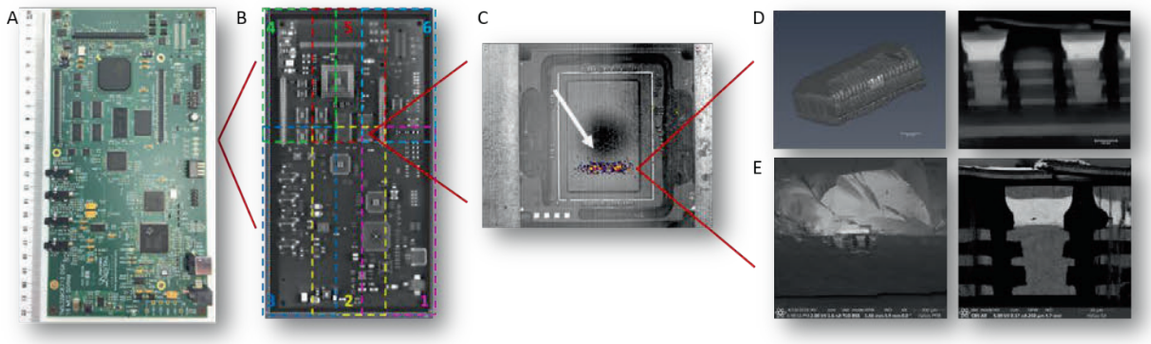

Figure 1: A) Examined PCB sample, B) uCT image of full PCB sample with indicated location of multiple ROI scans, C) IR thermography based defect location detection D) uCT based 3D and 2D visualization of the sample volume containing the defect and E) PFIB ASV based image collection at the defect location

Image-Based Control and Characterization of Lithium-Ion Batteries and Materials

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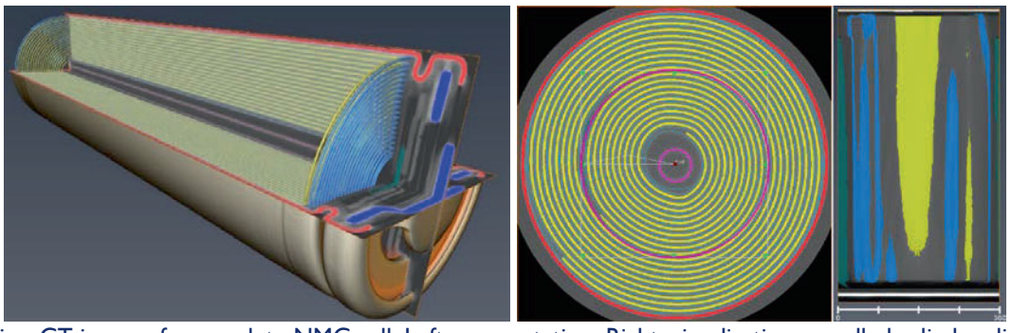
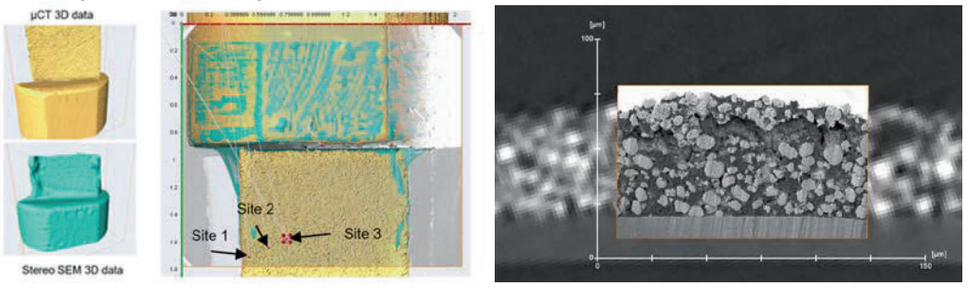
The research, development and quality control of batteries and fuel cells can benefit much from imaging. From X-ray Computed Tomography (CT) to FIB-SEM (Focused-Ion Beam – Scanning Eletron Microscopy), including recent Plasma FIB, images can be acquired to display the whole assembly, down to the microstructure of the materials involved.
MicroCT allows non-destructive image acquisition of complete cells. This allows for characterizing the sample for controlling the production process, or to monitor the evolution of the structure after specific usage conditions. We present analyses carried out on a NMC energy cell, scanned in its entirety at 7µm resolution. We propose visual inspection techniques accounting for the specific cylindrical and spiral geometry, and methods and results for segmenting the main components, and quantifying the thickness, surface, height and length of rolled electrodes.
Using Electron Microscopy (FIB-SEM), high resolution images can be acquired which can reveal the structure of the electrodes or the separator. Besides the volume fraction or surface areas of the different phases, the connectivity of pores and/or particles, their surface of contacts, path tortuosity or constrictivity, permeability or molecular diffusivity, become accessible.
Especially in batteries and cells, macroscopic properties - electrical, but also thermal and mechanical – find their origins at a micro- or nano-scale. Such multimodal correlative workflows allow investigating the multiscale nature of these properties, but also to investigate specifically defects that can be detected at the microCT level. We will present a correlative experiment, performing first a microCT scan of a cathode foil sample on its aluminium collector, spotting sites of interest in it, and acquiring those volumes with FIB-SEM.



MicroCT image of a complete NMC cell. Left: segmentation, Right: visualization, unrolled cylinder slice
Data aqcuired in the scope of a collaboration with the Electrochemical Innovation Lab, UCL.



Correlative microCT-FIBSEM study setup and approximately aligned datasets

Session 4: Medical and Forensics

How Engineers Helped Solve The Body in a Suitcase

Mark Williams

University of Warwick

On12th May 2014 partial human remains were discovered in a suitcase during routine maintenance work on a Birmingham canal. A thorough search of the surrounding area resulted in the recovery of a 2nd suitcase containing the remainder of the body of the deceased; Michael Spalding. Enquiries led the investigation to a former landlord and local property. However, physical evidence tying the suspect to both the scene of the crime and Murder was proving particularly difficult. That is, until the study of the contents of a recent bonfire and discovery of a suspicious looking lump of charcoal. This is the story of how Researchers based at WMG, the University of Warwick were called upon to help solve the case and provide Critical Evidence that eventually led to the convictions of Simon Lorenzo and partner Michelle Bird. The talk will describe how, for the first time, a combination of Micro-CT, 3D visualisation and 3D printing was used in such a high profile Homicide case and to produce evidence presented to a UK Jury. As well as drawing a large volume of media attention, the case has since featured in the documentary series 'Robbie Coltrane's Critical Evidence' and an appearance on Crimewatch at the BBC. The talk will also expand on how this breakthrough case has been used as the basis for creating a Forensics research hub for the application of MicroCT for the investigation of Homicides and provided expert evidence to support over 80 cases.

Morphological Substrates for Atrial Arrhythmogenesis in a Congenitally Malformed Heart with Atrioventricular Septal Defect

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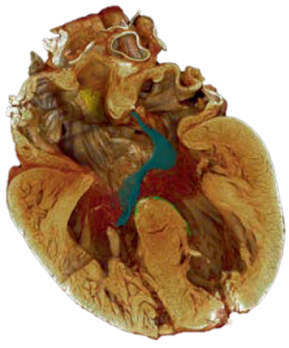
Keywords: *Micro-computed tomography, myocyte orientation, mathematical modelling, arrhythmia, atrial fibrillation (AF), re-entry, congenital heart disease (CHD), Atrioventricular septal defect (AVSD)*

Due to advances in corrective surgery, congenital heart disease has an ever growing patient population. Atrial arrhythmias are, however, frequently observed pre- and post-surgical correction. Pharmaceutical antiarrhythmic therapy is not always effective, therefore many symptomatic patients undergo catheter ablation therapy. In patients with atrioventricular septal defects (AVSD), ablation therapy itself has mixed success; arrhythmogenic recurrences are common, and due to anatomical displacement of the atrioventricular node, 3-degree heart block post-ablation is a real concern. In order to develop optimal and safe ablation strategies, the field of congenital cardiac electrophysiology must combine knowledge from clinical electrophysiology with a thorough understanding of the anatomical substrates for arrhythmias.

Using image-based analysis and multi-cellular mathematical modelling of electrical activation, we show how the anatomical alterations observed in hearts with an AVSD serve as arrhythmogenic substrates. Using ex-vivo contrast enhanced micro-computed tomography we imaged post-mortem the heart of a 5 month old male with AVSD at an isometric spatial resolution of 38 µm. Morphological analysis revealed the 3D disposition of the cardiac conduction system, the specialised cells responsible for generating and propagating the wave of depolarisation, for the first time in an intact heart with AVSD. We observed displacement of the compact atrioventricular node inferiorly to the ostium of the coronary sinus. Myocyte orientation analysis was performed using eigen-analysis of the 3D structure tensor, and revealed that the normal arrangement of the major atrial muscle bundles was preserved but was modified in the septal region. Models of electrical activation suggest the disposition of the myocytes within the modified atrial muscle bundles, together with the displaced atrioventricular node, serve as potential substrates for re-entry and atrial fibrillation.

This study used archived human hearts, showing them to be a valuable resource for the medical and engineering communities, and opening new possibilities for the investigations of arrhythmogenesis and ablation strategies in the congenitally malformed heart.



Volume rendering of a heart with AVSD, derived from contrast enhanced micro-CT image data.

Colonic Cycloramas for the Study of the Early Stages of Colorectal Cancer: Advanced Image Visualisation for Synchrotron-Based X-Ray Phase Contrast Computed Tomographic Data

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[2] Clinical and Experimental Sciences Academic Unit, Faculty of Medicine, UoS
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Introduction - Colorectal cancer (CRC) is the third most lethal cancer worldwide [1]. Aberrant crypt foci (ACF) are the earliest microstructural signs of CRC development on the colonic lumen [2, 3]. Researchers identify ACF *in vivo* through high-magnification chromoscopic colonoscopy (HMCC), where the lumen is sprayed with a dye (usually methylene blue) to reveal ACF [3] (Figure 1). A critical clinical question is whether an ACF identified through HMCC is related to dysplasia in histology sections of tissue biopsies, which directly correlates to increased risk for CRC development [4, 5]. However, the correlation of the morphology of ACF with microstructural characteristics deeper in the mucosa, has not been established [5-7]. If this was possible, the appearance of ACF in HMCC, could indicate the existence of dysplasia in histology.

Hypothesis - X-ray micro-computed tomography (μCT) could be employed to identify microstructural

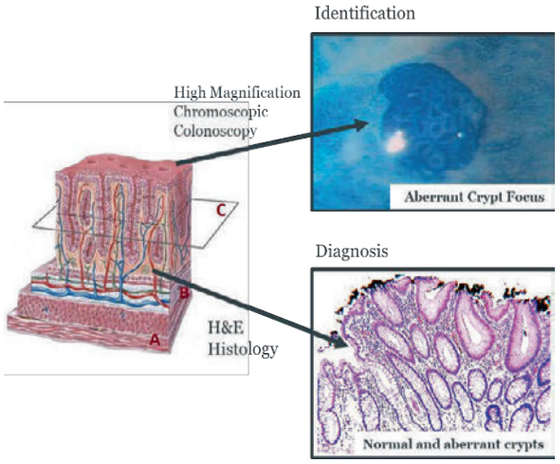

Figure 1: *Aberrant crypt foci are identified on the lumenal surface as clusters of abnormal tube-like glands and confirmed through standard Haematoxylin & Eosin staining.*

abnormalities and establish the correlation between the morphology of ACF and structurally abnormal crypts deeper in the mucosa (Figure 2).

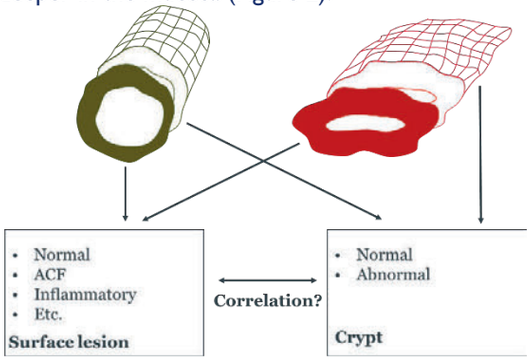

Figure 2: *Correlation between the appearance of lesions on the lumenal surface and structural abnormalities of crypts deeper in the mucosa.*

Materials and methods - Progressive stages of CRC have been chemically induced using a mouse model [8, 9] and synchrotron-based X-ray phase contrast μCT has been employed to reveal the three-dimensional microstructural details in unstained formalin-fixed paraffin-embedded colons. Here we present a digital signal processing technique developed to create panoramic views of the gut (colonic cycloramas) in order to identify the crypts. Surfaces perpendicular to each crypt in the tissue are defined using the μCT stack, which is then sampled across these surfaces to create cycloramas (Figure 3).

Results and outlook – Perpendicular crypt cross sections appear as circular profiles in cycloramas. Crypt lumens are distinctively darker, enabling the identification of the lumens by thresholding (Figure 4). This

automatic identification now allows us to quantify the morphology of the crypts and establish the correlation between ACF morphology and structural abnormalities deeper in the mucosal layers (Figure 2).

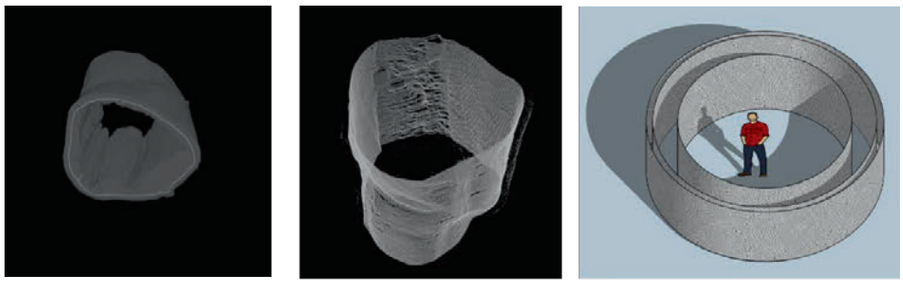

Figure 3: *Colonic cycloramas of normal mouse colon: The µCT stack is used to define surfaces that run throughout the tissue and are perpendicular to each crypt (left). These surfaces (middle) are used to sample the µCT stack and create colonic cycloramas, which are panoramic views providing an overview of the entire sample (bottom).*

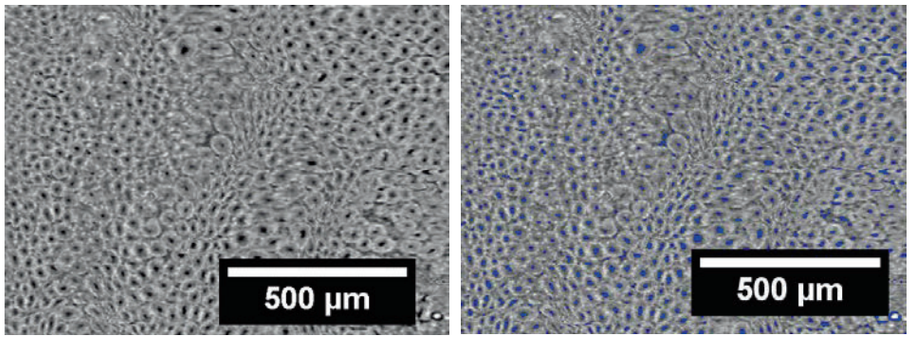

Figure 4*: Colonic cycloramas used for identification of the crypts. Perpendicular cross sections of the crypts appear as circular profiles in cycloramas, where the crypt lumens are distinctively darker (left). Simple thresholding of the grayscale cycloramas yields the crypt lumens, shown with blue colour (right).*

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High-Resolution X-Ray Tomographic Characterization of Hierarchical Multiscale Nanofibrous Scaffolds for Tendon Tissue Regeneration

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Keywords: *Electrospinning, Tendon tissue engineering, High-resolution x-ray tomography, Cell viability*

Regeneration of tendons represents an unsolved clinical problem. Resorbable electrospun nanofibrous scaffolds mimicking the morphology and mechanical properties of tendon fascicles were developed in a previous study [1]. The aims of the study are: (i) to develop a multiscale nanofibrous electrospun scaffolds mimicking the hierarchical morphology of a tendon; (ii) to characterize their structure with high-resolution x-ray tomography; (iii) to evaluate their mechanical properties and cell viability.
Electrospun bundles of aligned nanofibers of poly-L-lactic acid (PLLA) were produced by wrapping them on a drum collector [1]. To produce the multiscale tendon-like scaffold 100 bundles were aligned together. An "epitenon-like" sheath of PLLA was electrospun on the bundles to join them together. The morphology of the multiscale scaffolds was assessed with scanning electron microscopy (SEM) and high-resolution x-rays computed tomography (XCT). The orientation of the nanofibers was assessed following a validated XCT-based protocol [2]. Different voxel sizes of the XCT scans were chosen to enable a multiscale approach to the investigation (0.4-1.0 micrometers for the bundles, and 8.5-20 micrometers for the multiscale scaffolds). The mechanical properties of five multiscale scaffolds were tested with a monotonic ramp to failure with a physiological strain rate (100%/sec.). Cell infiltration was evaluated with human fibroblasts.
As expected, the nanofibers and the bundles showed diameters in the range of the collagen fibrils and fascicles in the human tendon [3]. The SEM and XCT images showed that the nanofibers were aligned within the bundles as desired, the sheath was homogeneous, and the bundles were compactly assembled. The XCT and SEM investigation confirmed also a morphology and hierarchical structure of the multiscale scaffolds similar to the human tendons [3]. The multiscale scaffolds showed a ductile behaviour with mechanical properties in the range of human tendons [3, 4]. Cells successfully infiltrated into the scaffolds and proliferated inside them.
The promising results for the produced hierarchical multiscale electrospun scaffold of PLLA confirm the potential of the production process developed in this study, able to produce high-fidelity scaffolds for regeneration and replacement of tendon tissue.

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Session 5: Bioengineering and Life Sciences

Metrology of Biofilms in Extreme Environments

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The biology-materials interface is an essential area of research since it influences everything from tooth decay to biological corrosion of petrochemical pipelines. Allied to this, the specification of the surface of any engineering component is important as this is the interface with mating components and/or the external environment.
Whether it is the increasing complexity and use of implant technology catalysed by the advent of new manufacturing technologies such as additive manufacturing, and the consequent arms race to overcome infection,

or indeed microbial induced corrosion in the oil and gas industries, there is a consequent demand for optimised and integrated characterization of the myriad aspects of the biofilm interface.
Work at Huddersfield has primarily focused on extreme environments exemplified by the presented case study outlining the role of biofilm activity in the deterioration of radioactive graphite and its disposal.
This case study combined visualisation techniques at different scales to build a full picture of the activity and growth of the biofilm in this case. The study utilised X-ray Computed Tomography to map porosity and extent of mineral deposits within the graphite material. Confocal Laser Scanning Microscopy was then used to image the organic composition of the biofilm which was found to be limited to the surface with no penetration into the porous surface. The formed biofilm was low in porosity and was found to be consistent across pH levels 9.5-11.0 with no release of ^{14}C.

None-destructive Imaging of Biological Structure in 3D

John Flynn

Carl Zeiss Microscopy

As X-Ray Microscopy is extended from the Synchrotron community to the laboratory, correlation to other imaging techniques is vital for many reasons. Partly due to the need to show where the technique fits in the landscape of multi length scale imaging and partly to show the efficacy of the application by correlating similar imaging modalities. We will show through various applications from the fields of life science how X-Ray microscopy complements existing technology, not replacing any technique, but adding further information to gain a deeper understanding of the scientific application.

Biophysical Comparison of the Outer Ear in Bush-Crickets (Orthoptera: Tettigoniidae): Pressure or Gradient Difference Receiver?

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Keywords: *Insect hearing, Exponential horn, Sound velocity, Pseudophyllinae, Copiphorinae*

The ear of bush-crickets consists of a system of paired eardrums (tympana) on each foreleg. The ear is backed by an air-filled tube, the acoustic trachea (AT), which transfers sound from the thoracic acoustic spiracle to the internal side of the eardrums. A key feature of the AT is its capacity to reduce the velocity of sound propagation and alter the acoustic driving forces at the tympanum by acting as a mechanical amplifier in some species. While the mechanism responsible for reduction in sound velocity in the AT is deemed to depend on adiabatic or isothermal conditions, its amplification role is related to the anatomy of the AT (usually a broad entrance at the acoustic thoracic spiracle, gradually narrowing as it reaches the tympana, type 1).

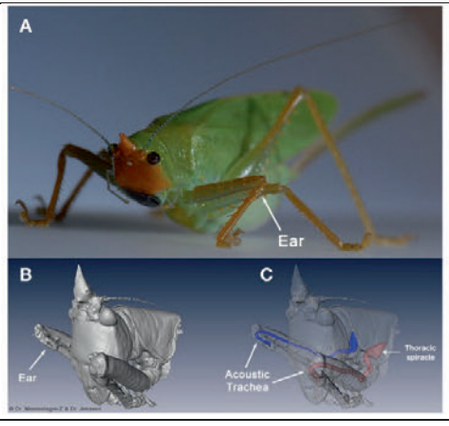

Fig. 1. Anatomy of the bush-cricket ear. A) A female of *Copiphora gorgonensis*, a model species for hearing research. B) 3D reconstruction indicating ear position. C) Transparent view of the specimen in B, showing the acoustic trachea (type 1) and acoustic spiracle position.

The combined mechanism of sound velocity reduction and amplification, and the fact that both tympanal surfaces are exposed causes a single sound signal to arrive twice at the same ear, externally at the normal speed of sound

in air, and internally with the sound propagation reduction imposed by the trachea. This mechanism is known as a pressure difference receiver. Nevertheless the acoustic trachea morphology varies enormously among the bush-cricket family, some of them having a very reduced spiracle and continuous diameter along its length (type 2). It is unknown whether both trachea types are used as a pressure difference receiver. To investigate the biophysics of these ears, we used micro-computed X-ray tomography and micro-scanning laser Doppler vibrometry. We measured the velocity of sound propagation and the transmission gains in the AT in two bush-cricket species with type 1 and 2 tracheae. Although both types of trachea reduce the speed of sound, only type 1 has the potential to enhance a pressure difference receiver system.

Mapping 3D Networks in Human Lung Tissue using Micro-Computed Tomography and Immunofluorescence

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Keywords: *Correlative imaging, Micro-computed tomography, Fluorescence, Human lung microstructure, 3D lung networks*

Micro-computed tomography (µCT) is a non-destructive imaging technique that can reveal the 3D lung microstructure. 3D networks in µCT images are generally identified and segmented by manually tracing their outline, which is very time consuming and requires specialist knowledge of the tissue. We devised a new method to segment 3D networks and specific cell types semi-automatically by correlating µCT imaging with immunofluorescence microscopy.

Using a prototype µCT system optimised for unstained soft tissues (Nikon Metrology, UK) we imaged unstained formalin-fixed paraffin-embedded human lung tissue at a voxel (3D pixel) size of 6-10 µm. The tissue was then sectioned and specific immunofluorescence staining performed at 20 µm intervals with primary antibodies for CK18 (airway epithelium) and CD68 (macrophages). Fluorescence microscopy images were digitised and registered to the µCT data.

The blood vessel network was semi-automatically segmented using the µCT data and a region growing tool in the open source itk-SNAP software package (http://www.itksnap.org). Immunofluorescence staining was successfully distinguished from the background autofluorescence on paraffin-embedded lung tissue by using a far-red (>650 nm) emission secondary antibody. The autofluorescence was used to align the two-dimensional (2D) fluorescence microscopy to the three-dimensional (3D) µCT images using the BigWarp plugin in ImageJ (https://imagej.net/BigWarp). The aligned immunofluorescence images indicated the specific location of airway epithelium in the 3D lung volume and were used to semi-automatically segment the networks and cells in the µCT. Gaps in the 3D network between the immunofluorescently stained sections were filled by digital interpolation guided by the µCT data using itk-SNAP. The segmented 3D network of blood vessels and airways can then be further related to the location of immune cells (macrophages).

In summary, correlation of 2D immunofluorescence and 3D µCT data permits localisation and segmentation of 3D lung networks and individual cell types in fixed human lung tissue. This novel correlative workflow allows for accurate, specific, and faster 3D network segmentation of human soft tissue.

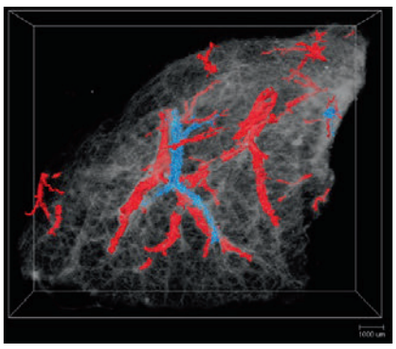

Figure 1: Semi-automatically segmented blood vessel network (red) using the region growing tool in itk-SNAP and airway epithelium (blue) from registered immunofluorescence staining within the µCT lung volume

3D X-Ray Histology by Means of Micro-Computed Tomography: A Streamline Workflow for High-Resolution 3D Imaging of Biopsy Specimens

Orestis L. Katsamenis[1*], Michael Olding[2], Jane A. Warner[2], David S. Chatelet[2], Mark G. Jones[3], Giacomo Sgalla[3], Bennie Smit[4], Oliver Larkin[4], Ian Haig[4], Luca Richeldi[3], Peter M. Lackie[2], Philipp Schneider[1,2], Ian Sinclair[1]

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Keywords: *Micro-Computed tomography, Histology, Human lung microstructure, Correlative Imaging*

Historically, micro-computed tomography (µCT or microfocus computed tomography) has been considered unsuitable for histological analysis of wax-embedded soft tissue biopsies due to the lack of contrast between the tissue and the embedding medium. However, we recently demonstrated that µCT can successfully resolve microstructural detail [1] of routinely prepared tissue specimens, which can overturn previous erroneous understanding of disease pathogenesis [2].
Here we demonstrate for the exemplar of human lung biopsy specimens a non-disruptive µCT imaging approach, adding truly 3D microstructural data of standard non-stained, formalin-fixed and paraffin-embedded soft tissue biopsies ('3D X-ray histology') to conventional 2D histology images obtained from the very same tissue blocks (cf. Figure). This approach does not interfere with conventional histopathology workflows but can augment, complement and go beyond (bio)medically/diagnostically relevant information obtained in 2D histology, by providing a full 3D context and revealing structural tissue connectivity and heterogeneity properties inaccessible in 2D histology.
This was achieved by optimised µCT imaging protocols developed in-house using the first-of-kind µCT scanner for 3D X-ray histology (Nikon, Med-X prototype). 3D X-ray histology achieved consistent and reproducible image quality characteristics at (isotropic) voxel size that ranged from 4 -10 µm, enabling qualitative inspection and quantitative image-base characterisation of the tissue. The volumetric nature of µCT data also allowed for precise co-registration of 2D histology sections with 3D µCT data sets and hence supplementing conventional 2D histology images, in order to investigate the complexity of soft tissue microstructures in a realistic and close-to-native 3D context. Furthermore 3D X-ray histology can be readily applied to a plethora of archival materials and routinely-processed tissue samples, yielding unprecedented opportunities for data mining via digitising archival tissue. Importantly, 3D X-ray histology offers fits seamlessly into existing histology workflows, which is pivotal for further uptake of this novel imaging technology by biomedical researchers and clinicians.

References:

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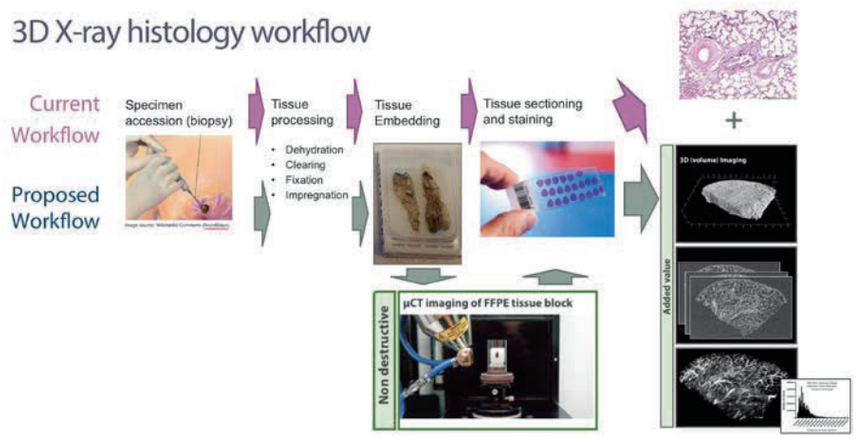

Session 6: Understanding Materials

In-situ and Operando Synchrotron Tomographic Characterisation of Semi-Solid Processing

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The processing of semi-solid material systems controls their microstructure and hence their final functional and structural properties. To optimise these final properties, we need to understand and quantify these materials microstructural evolution *in situ* and *operando*. Ideally, we would characterise microstructural features as we alter the processing conditions in real time, providing instantaneous feedback rather than costly trial and error experimentation. Using a unique process replicator (called the P2R) the complex thermal and mechanical processing of semi-solids can be simulated while real time characterisation is performed using synchrotron tomography or diffraction. This allows micron scale spatial resolution tomographs at a frequency of up to 1 Hz at synchrotron sources like Diamond Light Source.
We will demonstrate the benefits, and limitations, of using a process replicator to capture the evolution of microstructure in a range of systems from light weight alloys for transport applications to the solidification and deformation of cobalt based superalloys. Further, the flexibility of the system is demonstrated by applying it to image the flow of molten magma.

Multiscale Correlative Characterization of Environmentally Assisted Crack Initiation, Propagation and Failure in a High Strength Aa5083 H131 Alloy

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***Keywords**: X-Ray CT, AA5xxx, Environmental Assisted Cracking, IGC, Electron Microscopy*

Environmentally assisted cracking in a high strength AA5083 H131 alloy has been investigated using a multiscale correlative characterization approach to understand the surface intergranular corrosion to environmentally assisted crack (EAC) transition. Time-lapse 3D synchrotron X-ray tomography was employed during slow strain testing of a sensitized AA5083 sample sensitized at 80 °C for 250 h. In addition, several of the specimens tested were pre-exposed to a chloride containing environment to induce corrosion sites which could act as 'realistic' stress raisers in the subsequent straining. Reconstructed volumes of the X-ray CT time-lapse series allowed us to track and follow crack propagation in the material during slow strain rate testing at high resolution <5 µm. Volumes of interest from the test samples identified from the X-ray CT reconstructions were further analyzed post-mortem using electron microscopy and spectroscopy based techniques to study the presence and chemistry of secondary phases such as those based on Mg-Si, and their role in the initiation, propagation and/or arrest of crack tips/fronts.

Application of XCT to Steelmaking – Building up the Big Picture

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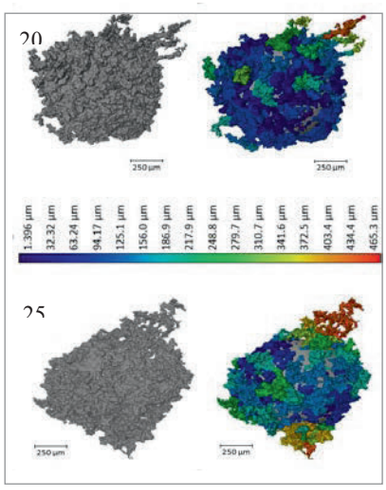
***Keywords**: Steelmaking, Metal processing, Reaction Kinetics*

The large scale production of the steel industry presents significant challenges with regards to control, measurement and prediction of performance. A typical Basic Oxygen Furnace (BOF) processes between 250 – 350 tonnes of liquid hot metal in a single batch and as such the application of laboratory X-ray Computed Tomography (XCT), with its limitations of volume and material penetration, can seem stretched for potential utility to say the least. Despite this, recent progress on the understanding of the BOF, through pilot-scale sampling and the generation of a droplet driven reaction process has presented opportunity to exploit XCT as an invaluable tool in the development of dynamic control models and fundamental understanding of the transient phenomena which occur during refining.

Samples taken from a 6ton pilot BOF from both the liquid metal bulk bath and gas/slag/metal emulsion have been analysed for porosity and droplet geometry respectively. These measurements along with the development of a reactive BOF model have allowed for the allocation of decarburisation contribution to the 3 "reaction zones" within the BOF. Further interrogation of droplet refining by combining High-Temperature Confocal Scanning Laser Microscopy with XCT has drawn attention to the transient phenomena of spontaneous emulsification within the system. The ability to use high-resolution XCT scans and in-situ observation of the pathway of interfacial perturbation, necking and budding into a dispersed emulsion has allowed for quantification of the slag/metal interfaces through the phenomena life-cycle and energetic rationalization of its occurrence. These findings present key insights and knowledge to build understanding in key areas for improved control and performance of this large scale industrial process.



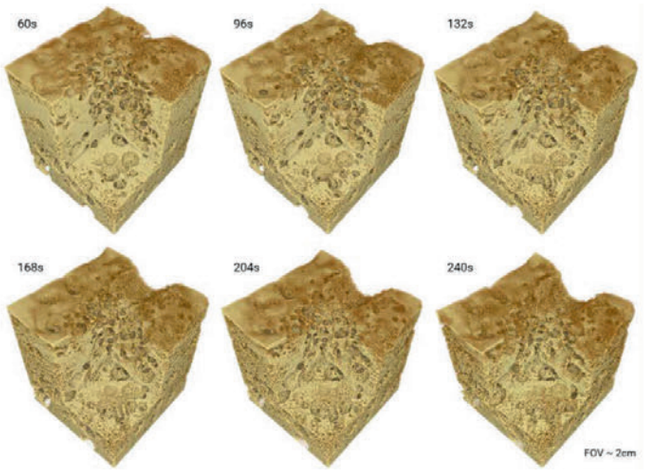
Understanding Materials Evolution Using Dynamic X-Ray Imaging in the Laboratory

Arno P. Merkle, Jan Dewanckele, Marijn Boone, Denis Van Loo

TESCAN XRE, Ghent, Belgium

Keywords: *Dynamic imaging, Deformation, X-ray mCT*

Time-resolved 3D imaging with X-rays has rapidly emerged as an essential technique to understand materials evolution, facilitating *in situ* investigations ranging from mechanical deformation to fluid flow in porous materials and beyond. This push toward time-resolved dynamic studies has been spearheaded by synchrotron radiation facilities, with temporal resolutions going below 1 second for a full 3D acquisition. Meanwhile, in the laboratory X-ray imaging has steadily improved, approaching spatial resolutions achieved at many synchrotron facilities. However, these tremendous gains have often come at a significant cost of temporal resolution. Recently, developments at XRE have made it possible to explore dynamic processes in the laboratory, achieving tomographic temporal resolution below 10 seconds. Here we explore the innovations that have led to this capability, including hardware design optimization and significant software advances in acquisition, reconstruction and analysis. Details of these methods will be illustrated by way of a foam collapse study. Formation and movement of individual bubbles are monitored and analyzed over time, providing valuable insights on the stability of the overall foam structure.



Session 7: Acquisition Techniques

Advanced Image Acquisition and Analysis; Combining HeliScan MicroCT and Avizo Software

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Behind the huge successes that X-ray tomography experienced over the past decades, scientists and industrials appreciate that they can investigate their samples non-destructively, both visually and quantitatively. This ability to build knowledge from samples is fueled by evolutions of image acquisition hardware, reconstruction, and also of image visualization and analysis software.
Thermo Scientific™ HeliScan™ microCT is a tool which addresses the compromise between image resolution, scan time and imaging volume. It represents a technology change of the CT industry, as it is first commercially available high-resolution µCT instrument built on the principles of high-cone-angle acquisition and reconstruction. High image quality and low noise levels is made possible by a unique range of advanced scanning- and reconstruction techniques, even at low radiation dose and short scan times.
The versatility of the Heliscan micro-CT system enables researchers to examine high-aspect-ratio samples (1:10) in 3D, both sample sizes ranging from cm-scale to sub-millimeter scale, and resolution down to 400nm. Image acquisition performed in a guided workflow mode, allows the user to inspect multiple regions of interest within a sample, or image the entire volume.
Workflow mode enables scanning of multiple samples, where the vertical stage serves as a sample changer system, where scan settings and scan geometry is automatically adjusted for each sample. This allows effective experiment time management as well as for a direct multi-resolution object(s) examination, significantly extending the range of experiments that can be performed.
Thermo Scientific Amira-Avizo Software proposes a powerful and intuitive platform for visualization and analysis of 3D, but also multi-channel/spectral and/or time series data. It features abundant state-of-the-art image and data processing algorithms allowing researchers and industrials to develop and apply supervised or automated image analysis workflows. This allows to provide answers, within the same software interface, to either unique experiments or routine tasks.
Combining high fidelity imaging with advanced visualization and data processing software, allow for an optimal experience to generate knowledge from samples. This will be demonstrated through a variety of use cases from different fields including materials science, biomedical, life science and electronics applications, as well as an input for the optimization of the production processes in industry.

Enabling Temporal CT in the Lab Through Reprogramming Existing Machines

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Temporal micro computed tomography (CT) allows the non-destructive quantification of processes that are evolving over time in 3D. Despite the increasing popularity of temporal CT the practical implementation and optimisation can be difficult, especially in the laboratory where commercial black-box micro-CT instruments are normally used. In this presentation, we show how different flavours of temporal CT can be implemented in the laboratory by reprogramming existing machines. We demonstrate a new software extension for collecting a large number of tomograms automatically at regular intervals; this was used to provide a unique temporal insight

into the germination of a mung bean. We highlight how a CT machine can be automatically synchronised with an in-situ rig, for example to examine granular segregation. Finally we enable a new flavour of temporal CT on laboratory systems through 'golden-ratio' projection sampling. A stream of projections is acquired as crystals precipitate in a porous media, with subsets of projections reconstructed *ex post facto* with an iterative scheme to form a time series. This overcomes the limitation of needing to know *a priori* what the best time window to acquire the optimal number of projections for each scan is, and allows the number of projections in a reconstruction to be varied as the sample evolves. The example of barite precipitation also reveals subtle differences in spatial and temporal resolution. This work has wide application across a number of fields, allowing temporal insight into for example mechanical testing, following battery degradation and chemical reactions.

Complementary Non-Destructive Analytical Techniques for Materials Science Application: Neutron and X-Ray Imaging

Genoveva Burca

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Keywords: *Neutron imaging, X-ray imaging, Palaeontology, Biology, Archaeology*

The complementarity of the neutron and X-ray imaging can be exploited in different ways depending on sample composition and goals of the experiments. While neutrons demonstrate a high sensitivity for some light elements, the X-rays show a strong correlation of the attenuation with the atomic number. The interaction of neutrons with hydrogen and their ability to distinguish between hydrogen and deuterium with no radiation damage make neutrons a good probe for imaging organic specimens. Very recently experts from palaeontology and bioengineering communities had for the first time the opportunity to utilize neutron imaging for non-invasive investigations by running the first experiments in these fields on IMAT (Imaging and Materials Science & Engineering), the new neutron imaging beamline in UK, built at the Rutherford Appleton Laboratory. The aim of this talk is to emphasize the importance of neutron imaging work in revealing new aspects and providing new information about the samples in addition to those acquired through X-ray imaging.

4D Laboratory X-ray Microscopy for the *in-situ* Investigation of Drug Release in a Push-Pull Osmotic Pump Tablet

Hrishikesh Bale[1], Stephen T. Kelly[1], Will Harris[1]

[1] Carl Zeiss X-Ray Microscopy, Inc., Pleasanton, CA, USA

Depending on the specific treatment, modern oral drugs may be engineered as immediate-release, delayed-release, prolonged-release, or targeted-release. In contrast to immediate-release, the latter methods require complex formulation, packaging, and encapsulation so the initiation and release follows a specific profile.[1] Osmotic controlled release is an advanced approach which utilizes a semipermeable membrane enclosing the drug layers or combinations of drug and push layers. The membrane allows water into the tablet, but restricts outward flow to a laser drilled orifice. This has many advantages over other methods. It is less influenced by motility or differing pH along the GI tract, allows tuning drug delivery rates, and is effective with poorly soluble drugs. However, due to the complexity, these tablets are challenging to develop and manufacture. Today, designing a delivery system for a particular drug relies on theoretical models to compute the timing of delivery. These calculations require experimentally determined parameters from techniques like light microscopy and scanning electron microscopy (SEM) where observing the drug over time requires interrupted experiments and destructive sectioning.

X-ray microscopy is a powerful imaging technique that enables 3D non-destructive investigation. Its allows non-destructive imaging of internal microstructures such as void and particle distributions, including processing and manufacturing defects. In addition, it enables in-situ observations of time dependent changes in a sample. We present here results from an in-situ, non-destructive investigation performed on a model pharmaceutical tablet based on the push-pull osmotic pump mechanism. The tablet was exposed to water inside a custom in-situ stage simulating operation in the GI tract. Employing X-ray microscopy (XRM) in a computed tomography approach we performed 3D imaging at 4µm/voxel resolution at several time points over 18 hours, capturing the changes in microstructure as water enters and activates drug delivery. The imaging clearly resolved the osmotic membrane, the bilayer composition of the tablet, and the laser drilled orifice with high contrast. Furthermore, the drug delivery action was clearly visualized and quantitatively analyzed. The results highlight the advantages of

this technique and may ultimately help develop more accurate and efficient drug release mechanisms.

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[2] Malaterre V, Ogorka J, Loggia N, Gurny R., 2009. Approach to design push-pull osmotic pumps. Int J Pharm. 376 (1-2):56-62.

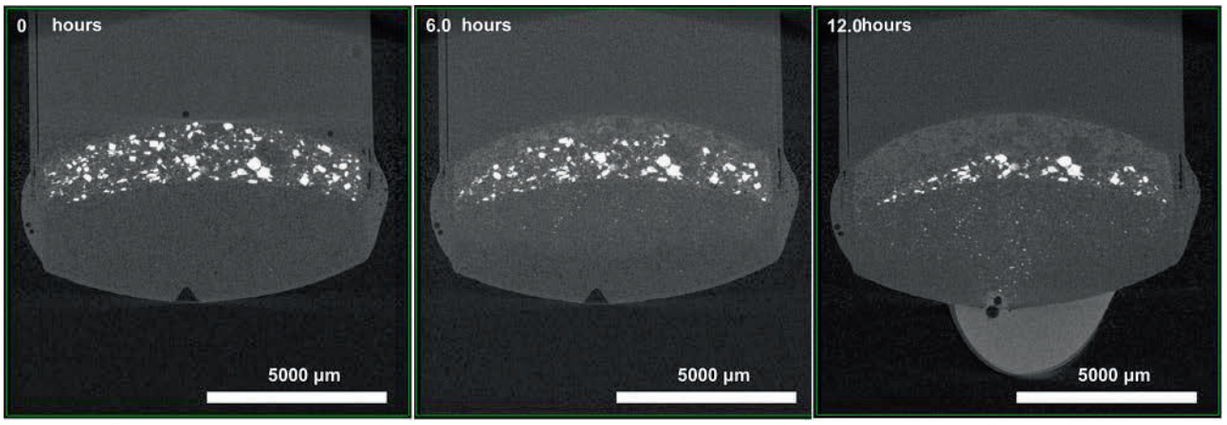

Figure 1. *Central cross-sectional slices from in-situ tomography data collected at 0 mins, 6 hours and 12 hours from the moment the tablet was immersed in water.*

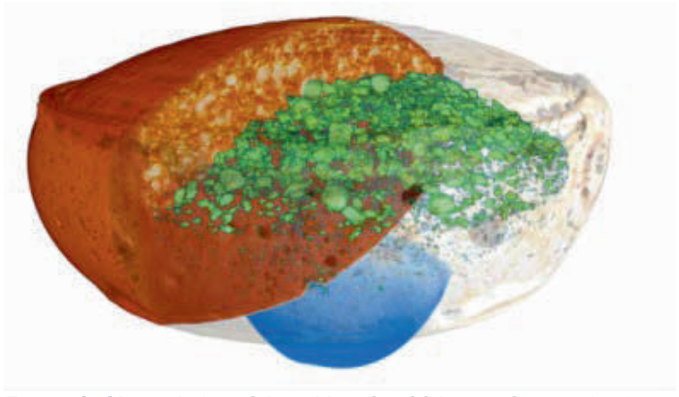

Figure 2. *3D rendering of the tablet after 10 hours of immersion in water. False colors were assigned in the 3D rendering showing push layer particles (green) and the released drug solution (blue).*

Full-Field Strain Analysis of Newly Formed Bone Induced By BMP-2 Loaded Hydrogels

Marta Peña Fernández[1], Cameron Black[2], Jon Dawson[2], David Gibbs[2], Janos Kanczler[2], Richard OC Oreffo[2] and Gianluca Tozzi[1]

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2. Bone & Joint Research Group, Centre for Human Development Stem Cells and Regeneration, University of Southampton, UK

Keywords: *Bone regeneration, Biomaterials, in situ X-ray microCT, Digital Volume Correlation*

Introduction. Biomaterial-mediated delivery of growth factors (i.e. BMP-2) to stimulate bone regeneration in critical sized defects represents a promising alternative to bone grafting techniques[2]. However, the ability of these therapies to produce bone mechanically comparable with the native tissue remains unexplored. This study examines the load-bearing capacity of newly formed bone produced *in vivo* following BMP-2 release combining *in situ* high-resolution X-ray computed tomography (XCT) mechanics and digital volume correlation (DVC).

Methods. Cylindrical bone defects were created in sheep femoral condyles: blank, autograft, InductOS and with nanoclay Laponite. InductOS and Laponite both incorporated BMP-2 growth factor. Ten weeks post implantation condyles were harvested and cylindrical samples (D=5mm, L=7mm) were cored from the defect areas. *In situ* XCT mechanics was performed applying three compression steps in the apparent elastic regime (1%, 2%, 3%), with images acquired at each step (5µm voxel size). DVC (final sub-volume of 40 voxels) was used to compute full-field strain throughout the newly formed bone.

Results. XCT images for Laponite (Fig.1a) and InductOS (Fig. 1b) showed considerable differences in the newly formed bone morphology. InductOS presented higher bone volume fraction and trabecular thickness (54.6%, 189.0µm) compared to Laponite (22.4%, 116.3µm). Significant deformation occurred in the Laponite at 3% global strain (Fig.1c), exceeding 10,000µε in most areas, whereas InductOS experienced levels of strains below 5,000µε and a more homogeneous distribution (Fig.1d).

Discussion. This is the first study that explores the relationship between mechanical and osteoinductive properties of biomaterials on the newly formed bone behavior using DVC. The BMP-2 delivery system applied appears to have a significant impact on the quality of the new tissue. In particular, Laponite experienced compressive strains well above typical values of trabecular bone yielding[3]. Future work is needed to fully understand the specific effect of each treatment on bone regeneration.

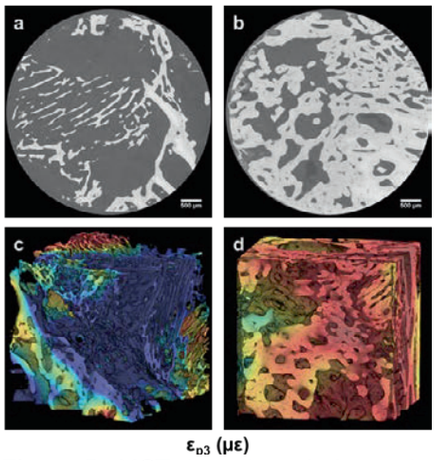

Figure 5. XCT slices through the newly formed bone and 3D full-field strain in the tissue at 3% global strain in Laponite (a, c) and InductOS (b, d).

Acknowledgment
BBSRC (BB/L021072/1 and BB/L00609X/1), and, MRC (G1000842 and G0802397) to RO. EPSRC fellowship (EP/L010259/1) to JID.

References:
1. Wang et al., doi:10.1016/j.bioactmat.2017.05.007
2. Gulberg et al., doi:10.1359/JBMR.090801
3. Bayraktar et al., doi:10.1016/S0021-9290(03)00257-4

Session 8: Cultural Heritage

Experiencing the World Beyond our Senses

Barnaby Churchill Steel

Marshmallow Laser Feast

Barnaby Steel from the art collective 'Marshmallow Laser Feast' gives us a behind the scenes look at his studios award winning virtual reality experiences and discusses the future potential of virtual reality to expand human perception, simulating experiences beyond the limits of our senses. His installation 'In the eyes of the animal' explores a forest through the senses of a mosquito, a dragonfly, a frog and an owl and uses LIDAR scanning to bring the real into the virtual. 'Tree Hugger, Wawona', Winner of the Tribeca Film Festival Storyscapes Award for Innovation in Storytelling takes viewers into the heart of a giant sequoia on the journey of water from root to crown. Collaborating with scientists and probing the limits of 3D scanning technology the work aims to expose the broader spectrum of reality to the masses through touring multi person immersive installations.

The Oxford Dodo: A Cold Case

Jay Warnett

WMG, University of Warwick

"Dead as a dodo" is a common idiom that proliferates the Dodo as an icon of extinction, having been discovered in 1598 and removed from existence just 65 years later. It was a flightless bird that was native to the island of

Maritius and met its demise at the hands of hungry sailors that visited the region. Given the short amount of time of its known being, documentary evidence both in behaviour and appearance is scant. Further, preserved remains of a single full Dodo skeleton do not exist – in particular only three Dodo skulls can be found across museum collections. What makes the Oxford Dodo skull particularly unique is that it is the only skeletal remnants with soft tissue. Given its historical importance and extreme rarity, the specimen was scanned using X-ray CT to create a digital record for conservation. With a full 3D reconstruction of the skull, FEA modelling was made possible to evaluate Von Mises stress under biting mechanisms to give an insight into how the Dodo fed and it's potential diet. But with closer inspection an unexpected discovery was made – a number of metallic "pellets" embedded within the skull. The historical record identifies the Oxford specimen as the Dodo seen by Hamon L'Estrange in London where people would come to see this exotic bird, but with no mention of its later killing. This opens up a number of questions about its origin and this particular Dodo's death that will further be discussed.

Micro CT of Large Fossils at the ESRF European Synchrotron : The Case of Mammal Forerunner Burrow Casts

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[2] ESRF - The European Synchrotron, 71 rue des Martyrs, 38000 Grenoble, France

Keywords: *Propagation Phase Contrast, Palaeontology*

The project presented here aims to define the biodiversity of burrowing vertebrates during the Permo-Triassic (PT) transition, marking the most dramatic mass extinction event occurring 250 Million years ago. As burrowing offers shelter against extreme temperature and humidity variations, the numerous fossil burrow casts found at the PT boundary are viewed as evidence of a key strategy used by vertebrates to cope with the harsh environment. Several fossilised burrow casts were investigated using Synchrotron Radiation micro Computed Tomography to test this hypothesis: If burrowing played an important role, it must be a common characteristic amongst surviving lineages.
A few burrow casts of 15 cm in diameter were characterised on the ID17 and BM05 beamlines with great success (120-170 keV, 50 microns pixel size). Whilst too few have been investigated to be significant yet, it has been shown that burrowing was used by all surviving lineages of mammal forerunners (i.e. Therapsids). Additionally, circumstantial evidence tends to indicate that some species were capable of entering deep torpor (e.g. hibernation, aestivation) to survive long periods of drought.
A larger burrow (30 x 20 x 60 cm) highlighted the current limitations of this technique for objects larger than 20 cm: on ID17, the fossil could fit in the field of view using the 350 micron pixel size germanium detector, but the coherence and resolution prevented detection of phase contrast fringes and fossil bones were barely visible. On ID19, offering a better coherence, several well preserved bones were detected, but the smaller size of the beam limited the results to a portion of the burrow (12 cm).
The new BM18 beamline being built as part of the ESRF's upgrade program should combine a larger field of view (60 cm) and better coherence, making it possible to finally include larger fossils in this study.

Understanding Blind and Partially Sighted (BPS) perception of Natural History Objects for 3D Printing Applications

Paul F. Wilson, M. Paul Smith, A. Attridge, Mark A. Williams

Keywords*: 3D Printing, Blind and Partially Sighted, Perception, Exhibition Design, User Experience*

3D printing is rapidly becoming a standard tool within the field of cultural heritage, being applied for a broad variety of purposes, including restoration, repatriation, research and visitor engagement among many others. The latter of these, that of engaging visitors with tangible 3D printed content is a subject that is understood to be very beneficial to museum visitor experience but is poorly understood. This is especially true of the blind and partially sighted, to whom the museum can often be an unwelcoming place dominated by purely visual display methods. 3D printing presents an opportunity to get around this issue and provide tangible experiences for the blind and partially sighted to help them engage with exhibition content. However, understanding of how to best design 3D prints for the blind and partially sighted is limited at this stage, few studies having explored the needs and considerations of the blind and partially sighted audience and how to best design 3D prints to aid the

interpretation and enjoyment of blind and partially sighted visitors. Here, we present a foray into understanding how the blind and partially sighted understand and interact with museum objects in order to understand how they interpret objects and what design considerations can be made in order to make such objects more easy to interpret. Analysis of one-on-one interviews shows that large scale features, shape and simple texture are readily interpreted but fine detail was rarely picked up on. Participants could accurately identify objects and materials and utilised multiple senses, particularly residual vision and sound. Object identification was primarily dependant on the participant's familiarity with the object. The implications of these findings are further discussed with regard to how they can be incorporated into the design of 3D printed replicas and exhibition design.

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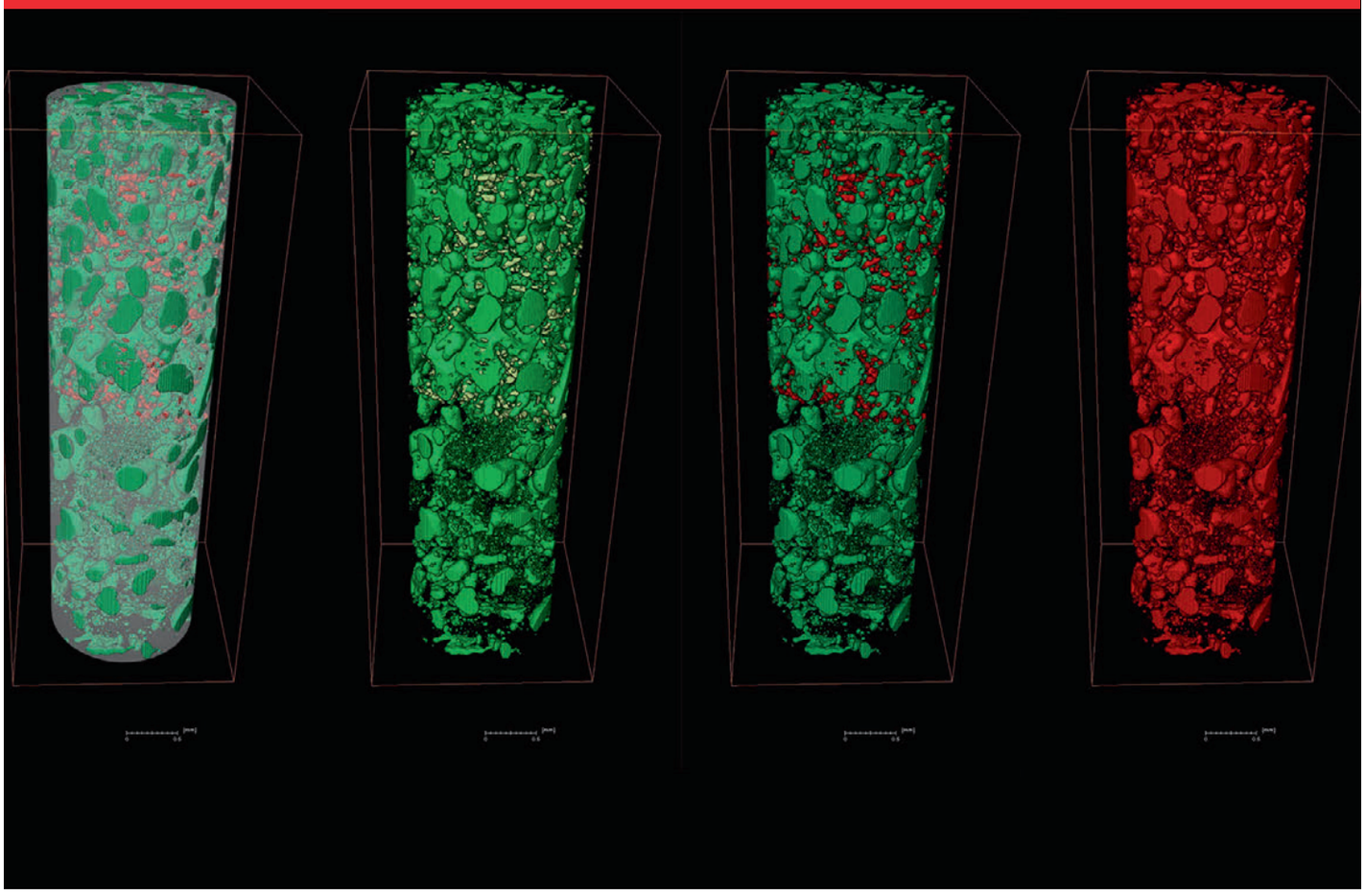

Additive manufactured CuAlZr-sample. Diameter ±1.5mm. Sample courtesy: Hamish Fraser, CEMAS, Ohio State University.

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Poster List and Abstracts

Poster List

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19 **Bioinspired lightweight vehicle design through advanced correlative microscopy**
Nicola Thomas, Swansea University

1

Dose Distribution From Micro-CT in Bone: A Case Study on the Mary Rose Remains

Sarah Aldridge[1,2], Dr Richard Hugtenburg[1], Dr Sarah Forbes-Roberston[1,3], Nick Owen[1], Dr Alex Hildred[4], Prof Richard Johnston[1],

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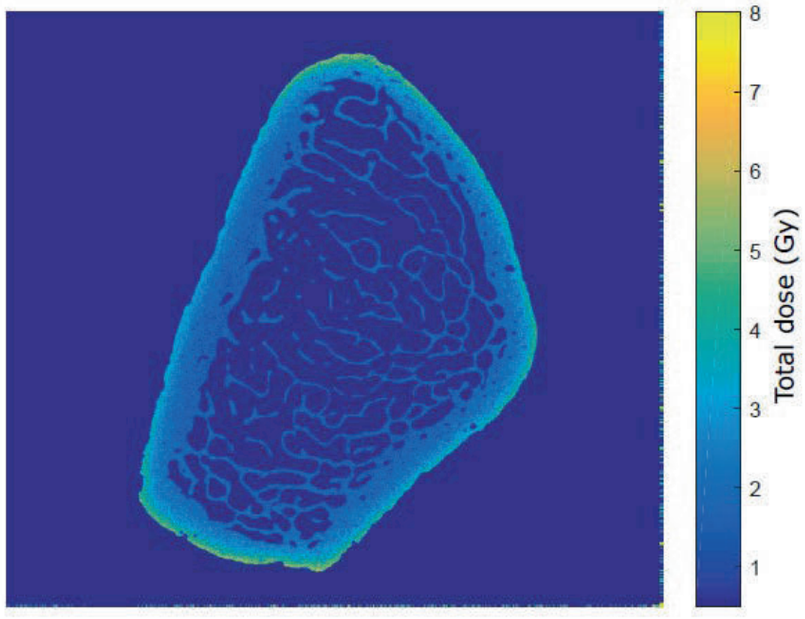
[2]Lincoln University
[3]Coventry University
[4] The Mary Rose Trust

Keywords: *Mary Rose, Dosimetry, Monte Carlo*

The Mary Rose is a Tudor warship that sank off the coast of Portsmouth in 1545, taking with her an estimated 300 crew members. In 1982, the Mary Rose was brought back to the surface, along with 90 almost complete skeletons, and many more unmatched human remains. The preservation of these remains is exceptional, but they are unique, precious, and susceptible to damage.
Micro-CT can provide a non-destructive pathway into extracting information from these remains, allowing for quantitative bone characteristics to be measured and quantified. With this wealth of information comes a consequence however, in the form of a radiation dose. This is of concern regarding downstream applications, but is difficult to truly quantify. Complex geometries can result in shielding, or increased exposures for certain regions, making traditional dosimeters and their single readings unsuitable. By running a series of Monte Carlo simulations to mimic the paths of photons and ionised electrons as they pass through the bone, it was possible to map the distribution of dose deposited onto the remains, and by standardising it against a dosimeter reading, establish a total dose. The dosimeter reading extrapolated to the length of a scan placed the dose at 2Gy; while the Monte Carlo simulation peaked at this value, it also found that much of the surface was receiving up to 4x this dose. These outer layers may contain valuable information in the form of delicate chemical or molecular data; by creating a map of dose distribution, it is possible to identify these elevated dose hotspots.



2

Using Micro Computed Tomography to Improve the Diagnosis of Strangulation Deaths- Validation and Initial Case Data

Waltraud Baier[1], Jason M. Warnett[1], Brian A. Burnett[2], Mark Payne[3], Mark A. Williams[1]

[1] University of Warwick, Coventry, UK
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[3] West Midlands Police, Police Headquarters, Lloyd House, Colmore Circus, Birmingham, UK

Keywords: *Forensic Imaging, Forensic Anthropology, Micro-CT, Trauma Analysis, Strangulation*

Strangulation is a common form of homicide but its diagnosis at forensic post-mortem is challenging due the reliance on external marks. Damage to the laryngeal skeleton can be indicative of strangulation but might be missed during autopsy if the injury is subtle or if it is not associated with haemorrhaging.
This study used micro computed tomography (micro-CT) to investigate cases of suspected strangulation. As the larynx has never been systematically examined at this resolution, an initial baseline study of intact specimens was conducted to determine the normal appearance. This was crucial to be able to understand and interpret any damage on the larynx or hyoid. Micro-CT scans of strangulation victims were subsequently compared against these baseline images. Using associated case information, an attempt was made to link the case circumstances with certain injury characteristics.
In general, the higher the level of force used, the more damage was observed on the scans. Ligature strangulations appears to have resulted in cartilage fractures more often than manual strangulations. Reconstructing the exact manner of death from the scans alone was not possible as there was some overlap in the fracture patterns.
It was found that overall micro-CT is a useful tool for identification of laryngeal trauma of bone and ossified cartilage, but produces limited results for soft tissue injuries due to low contrast. It should therefore be used in conjunction with other methods.

3

Correlative Imaging Techniques for Nanomechanical Testing Areas of Interest in Biomaterials

Rachel Board[1], Elizabeth Sackett[1], Ude Hangen[2], Jaroslav Lukes [2], Ria Mitchell[1]and Richard E. Johnston[1], Cameron Pleydell-Pearce[1]

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After millions of years of selective pressure, organisms in nature have evolved incredible structures that carry out beneficial functions and processes. The different levels of macro and micro organisation within the structure contribute to the functionality of the material. As a relatively recent species, humans have created structures and materials to satisfy their dynamic needs, which can involve energy and material intensive manufacturing approaches. Nature has been described as 'a school for scientists and engineers' (1), and it has not been until fairly recently that detailed research into biological materials for the purpose of informing engineering has increased our understanding and led to many bio-inspired designs. When investigating biomaterials, an initial understanding of the 3D microstructure prior to attempting to elucidate its mechanical properties is essential. X-ray microcomputed tomography (µCT) can image previously unseen or hidden internal structures of complex biomaterials; without the use of µCT scanning the presence of different phases, internal structures and defects such as cracks could go undetected. This is a problem because these features can impact the micro and nanomechanical properties of the material. With µCT internal structures will be observed non-destructively, and areas of structural and functional interest highlighted. For areas of interest to undergo nanomechanical property testing they must be exposed to the surface through careful sample preparation, which can be guided by the data obtained from the µCT scan images. This work investigates the challenges with bridging imaging and mechanical techniques within the same sample and developing correlative workflows to provide a multi-scale and multi-modal understanding of materials. Nanoindentation is used to determine nanomechanical properties, such as hardness and reduced modulus, of biomaterials which allows for an understanding of how these specific areas contribute to the structure-property-function relationships in the organism as a whole. As more bio-materials are explored and understood, this shapes the development of human-made materials to become more sustainable and better equipped for engineering, design, and architectural purposes.

Reference:
[1] Liu K, Jiang L. Bio-inspired design of multiscale structures for function integration. Nano Today. 2011 Apr 1;6(2):155–75.

4

Rediscovering the Museum's Treasures: µCT Digitisation of the Type Collection

Jonathan Brecko[1,2], Ulysse Lefevre[1], Camille Locatelli[1], Erik Van De Gehuchte[1], Koen Van Noten[1], Aurore Mathys[1,2], Marleen De Ceukelaire[1], Wouter Dekoninck[1], Annelies Folie[1], Olivier Pauwels[1], Yves Samyn[1], Danny Meirte[2], Didier Vandenspiegel[2] & Patrick Semal[1]

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Keywords: *Digitisation, Natural History Collections, Types*

At the end of 2016, the Royal Belgian Institute of Natural Sciences (RBINS), acquired two µCT scanners, through a budget of the Belgian Science Policy (BELSPO) to digitise it's precious collection. The two µCT scanners, a RX Solutions EasyTom 150 (http://www.rxsolutions.fr/) and a XRE UniTOM (https://xre.be/), with a resolution of 4µm and maximal power of 150kV, and a resolution of 500nm and a maximal power of 120kV respectively. It was a strategic choice to acquire two systems and not a two-in-one system as it speeds up the digitization process and allows scans to be made in case one of the machines is in maintenance. Besides the obvious time advantage, both machines complement each other. The EasyTom 150 is mainly used for specimens that are large or have a high attenuation, while the UniTOM most of the time is used to scan small or low attenuating specimens.
Given the size of the collection, approx.38 million specimens for RBINS, the focus of the digitisation project (DIGIT03) is on the type collection or similar precious specimens. Since the collection bares such a diversity in specimen composition, hardly any scan is like another one. Often it is also not clear what to expect as an outcome, as many of the specimens previously are only studied from the exterior or many decades ago when modern techniques were not available.
With this poster the first results and often unexpected surprises are presented, together with the challenges that come along while digitising a natural history collection using a µCT scanner.

5

Evaluating 3D Printing Software Using X-Ray Microtomography

Alexander Cresswell-Boyes[1], Asa Barber[2], Amo Tatla[3], David Mills[1], Graham Davis[1]

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Keywords: *Additive Manufacturing, Slicing Software, Open-Source, X-Ray Microtomography*

Objectives: In recent years there has been increased instances of desktop 3D printers due to the technological advancements made in additive manufacturing. One of the reasons for the increased instances, is the availability of open-source slicing software which controls the 3D printers. The aim of this study was to evaluate current open-source slicing software by imaging printed parts using X-ray microtomography.
Methods: A test part was designed using SketchUp and exported as a *.stl file into slicing software. Four open-source applications were evaluated: Cura, Slic3r, Repetier-Host, and Matter Control. Parameter settings including, layer height, wall thickness, and infill were kept the same and exported as a *.gcode file format to be subsequently printed. The parts were printed with a fused-deposition modelling printer using three separate materials; poly-lactic acid, thermoplastic polyurethane, and wood-PLA. Each print was carried out three times using the different materials for each software, a total of 36 parts were printed. Printed parts were imaged at 40 kV using the 'in-house' scanner at Queen Mary, creating high-contrast datasets. The reconstructed datasets were

analysed using ImageJ, quantifying dimensions, and volume, these were confirmed using digital callipers. Data analysis was carried out using Student *t-test* and One-way ANOVA.
Results: Reconstructed images showed voids in all the parts printed regardless of material or software. Visually Repetier-Host and Matter Control produced the worst replicas with the external and internal geometry lost. The wood-PLA composite proved to be the worst material, with each of the software failing to re-create the external geometry of the initial design. Data analysis showed that there was statistical significance (P<0.05) with all the software compared to the initial design.
Conclusion: The study has shown that Cura had the most consistent prints with Slic3r second, and Repetier-Host and Matter Control the worst, with PLA being a preferable material.

6

X-ray Nano-CT System with Nano-focus X-ray Tube and Hybrid-Photon-Counting Pixel Detector for Lifescience Applications

Tilman Donath[1], Tomi Tuohimaa[2], Emil Espes[2], Madleen Busse[3], Mark Müller[3], Simone Ferstl[3], Julia Herzen[3], Franz Pfeifer[3]

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[3]Department of Physics, Technical University of Munich, 85748 Garching, Germany

Keywords: *Computed tomography, Photon-counting, Pixel detector, X-ray Nanotube, Biomedical imaging*

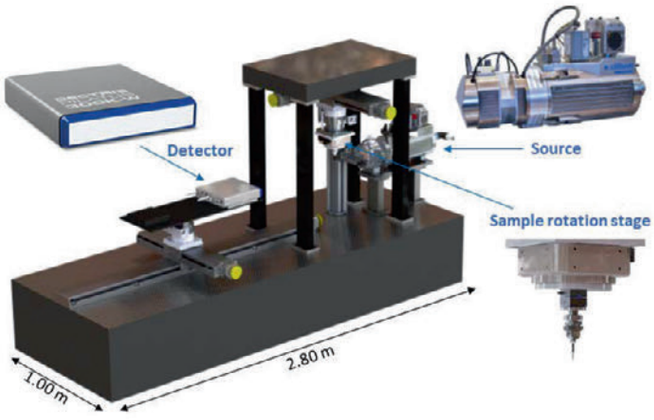

Figure 1. Nano-CT system at TU Munich: Hybrid-Photon-Counting pixel detector, PILATUS 300K-W (Dectris Ltd.), prototype Nanofocus X-ray source (Excillum AB), and sample rotation stage, installed on a damped optical table

An X-ray Nano-CT system (Fig. 1) has been developed at the Technical University of Munich for 3D imaging in life science research. Compared to commercial high-resolution CT systems, the system stands out through two novel X-ray components: a prototype nanofocus X-ray tube with a very small focal spot size (down to ~300 nm) and a pixel detector, which is virtually blur and noise free. The system uses strong geometric magnification (200 up to 2000-fold), with the sample close to the focal point of the X-ray source and the detector in comparatively large distance. This results to an achievable spatial resolution of about 100 nm. The spatial resolution of such an imaging system, is typically limited by penumbral blur caused by the finite size of the focal spot of the X-ray source. The size of the focal spot is limited by the design of the electron optics in combination with the design of the target. Furthermore, in order to achieve a high spatial spot stability, which is crucial in Nano-CT imaging, sophisticated cooling and shielding is required. We will present improvements that have been made in the electron optics, focusing technology, and development of a tungsten-diamond target for the applied prototype Nanofocus tube. The pixel detector is built in Hybrid-Photon-Counting (HPC) technology. Each pixel of a dedicated readout chip is directly bonded to a semiconductor X-ray sensor [1]. With a dedicated signal processing circuitry on each pixel, the energy of an X-ray event is analyzed and compared to a threshold energy. For events exceeding the chosen threshold, a digital counter is incremented by one. HPC technology makes the detector free of readout noise and prevents any accumulating dark signals, thus, even for long exposure times delivering images with highest signal-to-noise ratios. We will present the Nano-CT system and showcase results from the study of myoanatomy of a velvet worm [2] and the development of a specific X-ray stain for three-dimensional virtual histology [3].

Ivo de Sena Oliveira, Jörg U. Hammel, Henry Jahn, and Georg Mayer (Department of Zoology, Institute of

Biology, University of Kassel, 34132 Kassel, Germany) are acknowledged for their contribution to the velvet worm measurements.

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7

Multi-Channel and Advances Reconstruction Methods of the CCPi Core Imaging Library: An Open-Source Python Framework for Tomographic Reconstruction and Analysis

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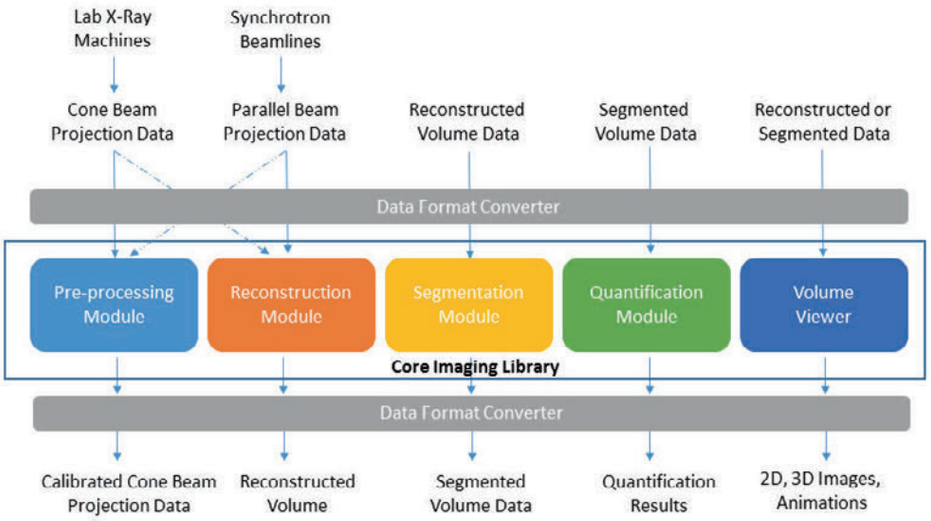
Keywords: *Tomographic reconstruction, Iterative methods, Multi-channel tomography, Software, Python*

The Core Imaging Library (CIL, http://cil.readthedocs.io/) is a set of modules for each process involved in the data analysis workflow of Computed Tomography (CT) datasets (see overview in figure). CIL contains data-processing modules which can be applied to the dataset prior to reconstruction, e.g., noise-removal filters and beam-hardening correction, as well as novel iterative reconstruction methods and segmentation and quantification methods. The motivation for creating this library is to provide the CT imaging community with a set of tools that are easily accessible and can be integrated into existing workflows such as SAVU of the Diamond Light Source.

The CIL framework is developed by the Collaborative Computational Project in Tomographic Imaging (CCPi, http://www.ccpi.ac.uk) with algorithm contributions from the UK CT community reengineered to make the code run faster, easily accessible and maintainable. The CIL is implemented in Python with some back-end parts in C++ and CUDA for faster parallel execution on different hardware architectures.

This presentation will demonstrate the capabilities of the CCPi CIL software for tomographic reconstruction of laboratory and synchrotron X-ray data as well as neutron data. A new modular object-oriented framework has been added to the CIL allowing users to easily experiment with a variety of novel reconstruction methods by mixing and matching algorithm components. Reconstruction of high-quality images from low-quality tomography data using the CIL will be demonstrated.

A new addition to the CIL reconstruction framework is the capability to handle multi-channel tomography data sets arising, for example, in hyperspectral tomography applications enabled by emerging novel photon-counting detectors. The CCPi Flagship project "A Reconstruction Toolkit for Multichannel CT" is developing novel reconstruction techniques to handle the low signal present in each channel and exploit correlations between channels and allow improvements compared to naïve channel-wise reconstruction. Examples of multichannel reconstruction will be demonstrated within the CIL framework.



8

Structural and Functional Characterisation of 3D Printed Pharmaceutical Dosage Forms by Means of High-Resolution X-Ray Computed Tomography

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Keywords: *Micro-computed tomography, Pharmaceutical Technology, Additive manufacturing,*

Fused filament fabrication (FFF) three-dimensional (3D) printing, a method used to produce objects in three-dimensional space by sequential deposition of layers of material, is being steadily deployed as manufacturing technology for the development of personalized pharmaceutical dosage forms. This technology enables production of dosage forms with complex geometries, allowing manufacturers to improve on pharmacokinetics and/or more accurately target delivery sites. This can be achieved either by incorporating pharmaceutically active substances into polymeric filaments used to 3D print the dosage form, or by 3D printing complex carriers (excipients) which encapsulate the drug for controlled delivery.

The adoption of 3D printing technology by pharmaceutical industry and research, created a need for alternative techniques able to characterise increasingly complex dosage form geometries. Here we demonstrate the use of such technology, namely X-ray microfocus computed tomography (μCT, micro-CT), to characterise in-house designed and 3D printed pharmaceutical formulations. The non-destructive high-resolution 3D (volume) imaging capabilities of μCT allowed us to conduct a wide range of characterisation studies. Specifically: [a] structural integrity of the 3D printed object by means of defect analysis; [b] quality control of the fabrication process accuracy by means of actual / nominal comparison, i.e. 3D printed object / CAD design of the object; [c] dissolution studies by means of ex-situ time-resolved μCT imaging (often referred to as 4D-CT)[1-3].

Our studies demonstrate that μCT can provide vital structural and functional insights of 3D printed pharmaceutical dosage forms and should be considered an indispensable tool in the pharmaceutical technology characterisation toolbox.

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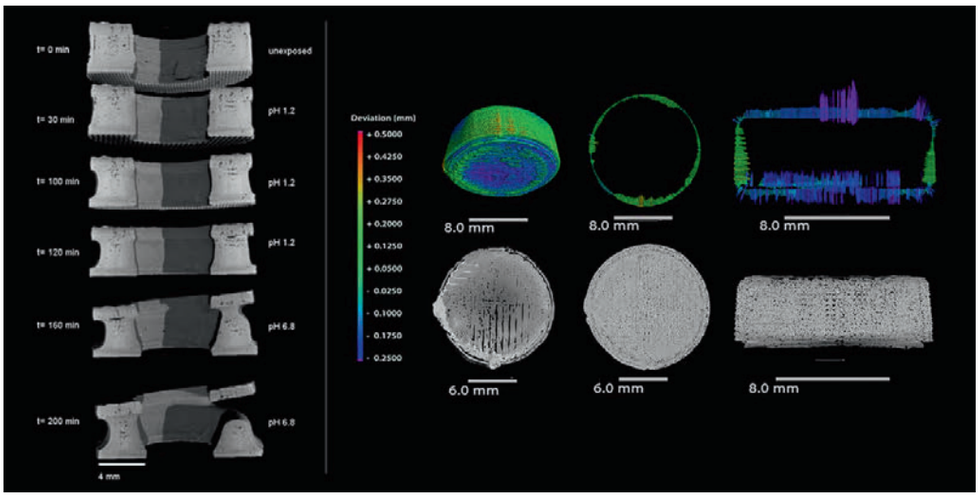

*(**Left**) time-resolved µCT imaging showing the volumetric changes of a doughnut-shaped printed dosage form during consequent exposure in media that simulated exposure to gastrointestinal environment; virtual cross-sectional view*
*(**Right**) Volume rendering of a solid printed dosage form showing the deviation map of printed object's surface compared to the nominal values of the CAD design*

9

Nanoscale Imaging of Gecko Skin: Translation to Biomedical Materials with Cell Control

Stephen T. Kelly[1], Gregory Watson[2], Kenneth Ka Ho Lee[3,4], Jolanta Watson[2], and David W Green[4]

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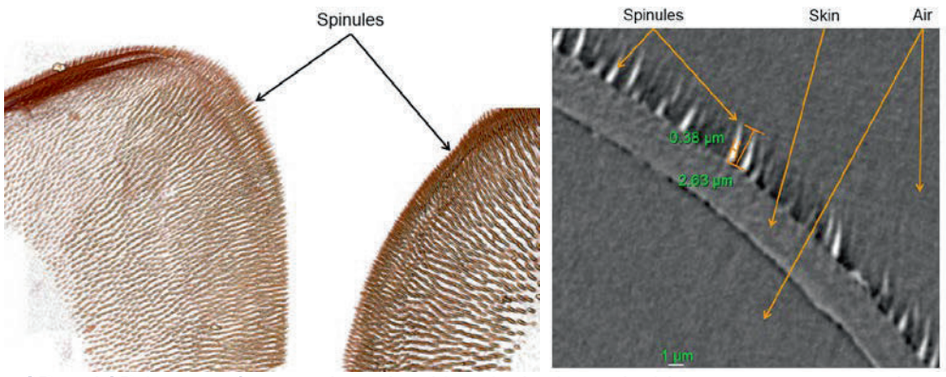
Nanoscale patterning is vital to advancing the design and function of biomedical materials. Nanostructures control the behavior of cells and provide a powerful means of influencing cell function. There is great interest in learning about the properties of natural materials to improve cell control and behavior. Human cells and microbial cells are affected by nanostructures, which can kill various bacteria. Exactly reproducing natural materials with high complexity is not a feasible option. Manufacturing nanoscale structures and architectures is possible with beam lithography techniques, but the achievable complexity is very limited. 3D printing has established itself as a powerful technology for creating biomedical objects, but the technology is currently limited to printing at the microscale.

High-quality digital imaging of natural nanostructures in 3D is promoting the development of 3D printing devices for nanoscale manufacturing. This represents a major step in translation between small natural objects and artificial print-outs. We present here laboratory-based 3D X-ray imaging results (ZEISS Xradia 810 Ultra) showing the complex 3D nanostructures on gecko lizard spinules. The accumulated X-ray data was converted to a digital representation of the gecko skin nanostructures with 3D image analysis software (Dragonfly Pro by ORS). We show here that the resolution of the spinules matches the original in all engineering criteria as well as the structural and morphological features essential in killing bacteria. The images were then transformed into 3D models that can be edited to create surfaces resistant to different bacteria strains.

Modeling cell interactions from 3D reconstructions is essential in optimising design to function. Digital imaging of complex nanostructures such as the gecko skin spinule array, is essential to recreate the intriguing naturally developed materials that carry out innovative physics and chemistry at their interface. The development of print heads with picometric droplets may eventually translate the nanostructures captured here in 3D into real world objects. As this becomes a reality, 3D X-ray nanoscale tomography will play an integral role in imaging and understanding these types of nanostructured materials.



3D and 2D images of nanoscale gecko skin spinules imaged with x-ray nanotomography.

10

Non-Destructive Micrometer-Scale 3D Imaging of Intact Fossil Specimens

Stephen T. Kelly[1], Hrishikesh Bale[1], Alyssa Browning[2], Mansoureh Norouzi Rad[2], and Will Harris[1]

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Investigating valuable or unique samples presents a unique challenge in analytical microscopy. These samples – whether one of a kind museum artifacts, fossils, or failed parts – should not be cut or sectioned unless the results justify sample destruction. As such, as much information should be gathered from these samples non-destructively as possible before considering destructive analysis. Furthermore, non-destructive analysis guide further sample manipulation for these valuable samples.

X-ray microscopy (XRM) allows for high resolution imaging (<4 µm/voxel) of comparatively large (>25 mm diameter) objects. Where conventional micro computed tomography (µ-CT) is limited to achieving high resolution images on small objects (~2 mm for 4 µm/voxel), x-ray microscopy overcomes these limitations through a flexible and optimized detector array. We present here results from imaging a small (<1 mm) spider encased in amber that illustrate the power of XRM for analyzing these types of specimens non-destructively at high resolution. An amber fossil ~20 mm in diameter containing a small spider was imaged on a laboratory x-ray microscope (ZEISS Xradia 520 Versa) without trimming the fossil. The sample was imaged with excellent contrast at voxel resolutions of 1.2 µm/voxel. The resulting images show fine details within the spider and how it is positioned within the amber fossil.

Two main conclusions come from this study. Firstly, the images provided by XRM are immediately useful to researchers hoping to see internal structures of the organism. Detailed measurements and identification of internal structures can be made with little effort. Secondly, the XRM results provide information about the fossil quality, location, and surroundings. This allows researchers to evaluate whether to extract the spider, how best to do this, and if other important regions may have been missed from an initial inspection. This information is especially important when handling and working with fossils and museum artifacts, but the ideas and workflow presented here are easily extended into other areas such as defect isolation and analysis in semiconductor research, or high resolution imaging in carefully developed biological specimens.

3D renderings of two ~1.5 mm sized insects encased in a ~20 mm diameter amber fossil

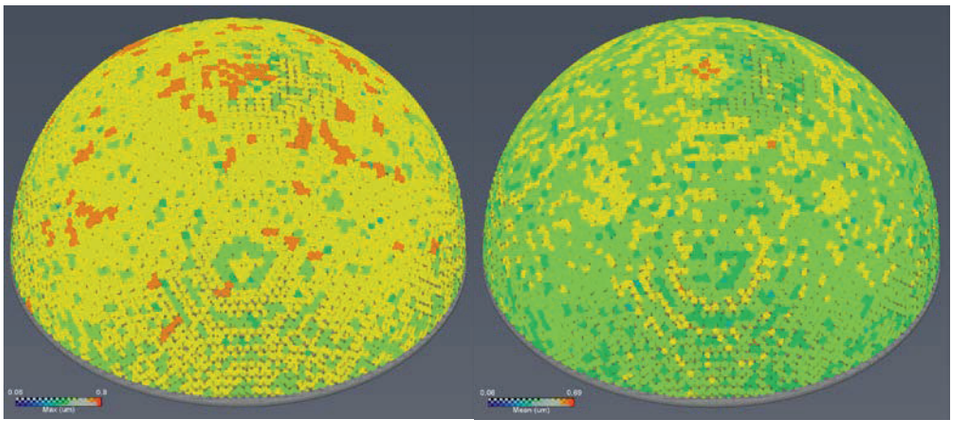
11

XCT Inspection of Lattice Structure of Acetabular Hip Prosthesis Cups

Nadia Kourra, Jay M Warnett, Mark A Williams

University of Warwick

Successful arthroplasty requires integration of the prosthetic implant with the bone to replace the damaged joint. Bone-mimetic biomaterials allow bone ingrowth and implant fixation due to their mechanical properties and porous structure. Modern hip prosthesis minimised the common severe complications of the past and maximised the service lifetime. Some complications related to arthroplasty including loosening, particle disease and infection are still common. The high quality of arthroplasty components need to be established before their utilisation in healthcare due to the medical implications and future complications that they can cause. X-ray Computed Tomography (XCT) is uniquely able to provide the required information in the assessment of these products. This presentation demonstrates the application of XCT in the inspection of the lattice structures that allows bone ingrowth. The results of this inspection include the examination interconnectivity and local thickness analysis of the lattice and pores. The results can be compared to previous studies that demonstrate optimum sizes of lattice structures and pores, and provide information of weak regions.



12

3D Quantification of Laminar Layup in a Bird Feather Shaft

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[1]University of Southampton
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***Keywords**: SRCT, layup, Tomography, Form:function*

Feathers have been evolving for more than 130 million years under selection pressures to become light, stiff and strong. However, detailed investigation into the internal material structure (and properties) of the shaft is still lacking. Previously, we have shown that the laminar structure of the feather shaft varies around its circumference and along its length. This is based on the observation of pseudo-ellipsoid voids, which can be observed with Synchrotron Radiation Computed Tomography (SRCT) at 300 nm voxel resolution.
After reconstruction and post-processing, the size, shape and orientation of these voids can be measured using the FIJI software package and the BoneJ plugin. Here, we present the orientations of these ellipsoids and map how they change with spatial location, thereby quantifying the laminar layup for the first time using a repeatable method. These results are an important step forward in understanding the form:function relationship of this complex structure in more detail.

13

Correlative Imaging of Plant-Soil Interactions: A Novel Multi-Modal and Multi-Scale Approach for Identifying and Interpreting Biologically-Mediated Weathering

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Keywords: *Correlative imaging, Soil, Weathering, FIB-SEM, Plant-soil interactions, Multi-modal, Multi-scale*

Correlative imaging provides an opportunity to understand the interactions and mechanisms involved in the structure of complex biological and geological systems by combining and utilising information across dimensions (e.g., 2D to 4D), modes (microscopy to tomography), and scales (centimetres to nanometres).
Here, we have used the correlative potential of numerous imaging systems: optical light microscopy (LM), scanning electron microscopy (SEM), high resolution X-ray microscopy (X-ray µCT) and focussed ion beam (FIB) microscopy to ascertain the structure and in-situ interactions present in cryptogamic ground cover (CGC) soils from Iceland. CGCs, often termed biological soil crusts, contain combinations of primitive early colonising plants and organisms, such as bryophytes (mosses, liverworts, hornworts), lichens, algae, fungi, and bacteria. Importantly, they are also considered modern analogues of early terrestrial plant habitats from around 450 million years ago, before the evolution of herbaceous plants and trees. The expansion of a primitive terrestrial biosphere had an influential effect on the architecture of river and sedimentary systems, soil development, and crucially the drawdown of atmospheric CO_2 through burial of organic carbon and weathering. Consequently, understanding the intricate interactions in modern CGCs can shed light on exactly how ancestors of these primitive organisms contributed to soil-forming processes, how they develop organism/plant – soil interactions, and how they promote weathering to create biologically-mediated soils.
Via high resolution X-ray µCT scanning of soil micro-cores, we have identified various interactions including curious ~5 µm wide probable biologically-mediated weathered tunnels within soil grains. In addition, we have utilised the correlative potential of Zen Connect and Atlas 5/3D software to combine 2D and 3D datasets; this has allowed specific 4D region of interest study via FIB-SEM.
The work demonstrates that multi-modal and multi-scale correlative workflows can be applied to complex sample types and can help inform about intricate biological/geological relationships.

14

Preservation of Bone Tissue with Temperature Control for *In Situ* SR-Microct Experiments

Marta Peña Fernández[1], Enrico Dall'Ara[2] Alexander Kao[1], Katerina Karali[1] Andrew J Bodey[3], Asa H Barber[1,4], Gordon Blunn[5] and Gianluca Tozzi[1]

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2. Department of Oncology and Metabolism and INSIGNEO institute for in silico medicine, University of Sheffield, Sheffield, UK
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4. School of Engineering, London South Bank University, London, UK5. School of Pharmacy and Biomedical Sciences, University of Portsmouth, Portsmouth, UK

Keywords*: Bone, Synchrotron microCT, Radiation-induced damage, Digital Volume Correlation*

Introduction. Digital volume correlation (DVC) combined with *in situ* synchrotron micro-computed tomography (SR-microCT) mechanics allows full-field strain measurement in bone at tissue level. However, long exposures to SR radiation induce bone damage [1] and experimental protocols able to preserve tissue properties are still missing, although recent progress has been made [2]. This study aims at proposing a proof-of-concept methodology to retain bone tissue integrity based on residual strain as a result of decreasing the environmental temperature during *in situ* SR-microCT testing.

Methods. SR-microCT imaging of bovine trabecular and cortical bone cylindrical samples was performed at I13-2 (Diamond Light Source, UK). Tomographic datasets were obtained at an effective voxel size of 0.81μm (1800 projections; 512ms/projection). Half of the samples were imaged at 23°C, and half at 0ºC. Thermocouples were attached to bone surface and used to investigate temperature during acquisition. Each specimen underwent five consecutive tomographies (zero-strain). DVC was carried out to evaluate the residual strain in the tissue due to progressive damage induced by X-ray exposure during SR-microCT imaging at different temperatures.
Results. Microcracks were clearly visible in trabecular bone after five tomograms at 23°C. However, decreasing the temperature to 0°C facilitated tissue preservation, as microcracks were not observed. Overall, higher strains in the trabecular specimen at 23°C were found (Fig. 1, top), compared to the specimen at 0°C (Fig. 1, bottom). No damage was detected in cortical bone tissue. Temperature readings suggest a consistent increase of temperature (ΔT=~0.4°C) at each opening/closing of the shutter.
Discussion. This experiment enables important understanding on the damage induced by SR X-ray radiation and the effect of heat generation on the bone tissue. Lowering the temperature seemed to reduce microdamage in trabecular bone, but minimal effect was observed for the cortical. Temperature gradient was small, although it may be sufficient to induce localized collagen dehydration and damage [3].

Acknowledgments
Diamond Light Source (MT16497)

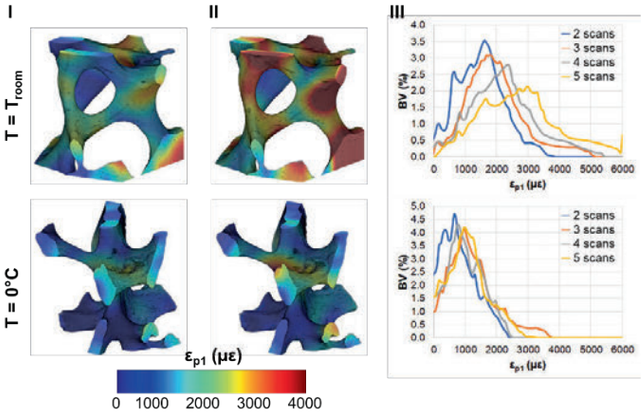

Figure 1. *First principal strains (ε_{p1}) in trabecular bone imaged at room temperature (top) and 0°C (bottom) for the second (I) and fifth (II) acquired tomograms. Histograms of the residual strain distribution (III) in the tissue after each tomogram are shown.*

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15

Study on Inclusions Causing Clean Steel Defects

Akalya Raviraj[1], Stephen Spooner[1], Nadia Kourra[1], Wouter Tiekink[2], Gert Abbel[2], Mark Williams[1], Sridhar Seetharaman[3], Zushu Li[1]

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[2]Tata Steel Europe
[3]Colorado School of Mines

Non-metallic inclusions (NMIs) cause various defects in steel such as Griffe Laminee and Split Flanges. The reaction between the NMIs and liquid steel in the continuous casting mould directly affects the inclusion behaviour such as its residence time & removal. However, there is lack of kinetic information on the NMI-steel reaction.
The inclusions in steel are small particles of reacted mould slag and/or reaction products from steelmaking processes. Mould slags are molten oxides (with or without fluorides) that are used to control lubrication and heat transfer during the continuous casting process.

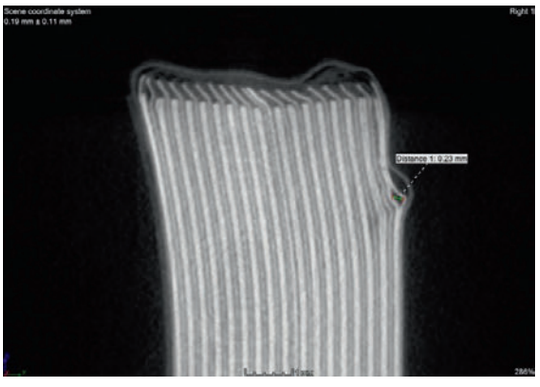
We are developing a novel approach, by combining High Temperature Confocal Laser Scanning Microscope (HT-CLSM), X-ray Computed Tomography (XCT) and advanced characterisation techniques, to study the kinetics of the NMI-steel reaction. HT-CLSM is an in-situ method can observe the behaviour of individual inclusions moving on the surface of the molten steel, including their nucleation, collision, agglomeration and pushing by interfaces. Pre- & post-experimental samples are scanned by using a XCT scanner. The XCT data is examined and analysed by using Avizo. XCT scanning of fast quenched sample can provide dynamic information of NMIs' removal in the liquid steel. Avizo analysis can segment the sample and examine features such as the size of the inclusion and any porosity, also giving numerical values. Advanced characterisation techniques will be employed to study the NMI-steel reactions in the solidified samples, particularly the element exchange between steel and NMIs. This technique can give compositions of the inclusion and the steel.
The knowledge created will be used to predict the residence time of the inclusions in the molten steel in the continuous casting process, which will help validate CFD models and optimise fluid flow in the mould. Ultimately, it will help produce clean steels by accelerating the removal of NMIs from liquid steel.

16
A New Approach of Analysis on Underperforming Battery using Micro Computed Tomography (µct) Technology

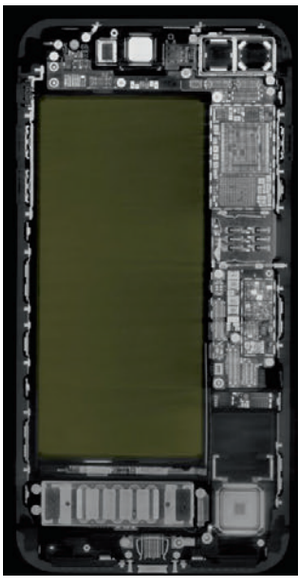
Dr G. Remy, Prof M. A. Williams, Dr M. Loveridge

University of Warwick

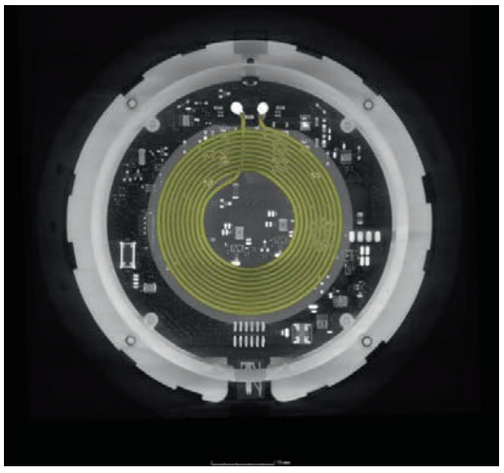
Batteries and energy storages are becoming ubiquitous in mobile gadgets, industries, electric vehicles. More than the visible consumer electronics application, energy storage plays a critical role in areas such as manufacturing, electricity generation and transportation. Portable devices are becoming more and more common, so battery efficiency is getting a very important part of the device design. To determine the reason of an underperforming device is often a challenge; usual non-destructive technics aren't providing a full 3D interpretation of the internal parts of the device, dismantle/destructive technics allows a complete view of the inside but brings physical stressed due to the manipulations. Micro Computed Tomography (µCT) technology would bring the best of the two by allowing the user to visualise the internal structure of the sample without cutting or dismantling the specimen.
The presentation is providing evidence of the benefits of using non-destructive X-ray µCT technology to analyse key components to confirm defect within the microstructure such as (delamination within the layers, welding integrity, inclusion within the separators…). On the poster, specific example, such as the Samsung Galaxy 7, fitBit flex and the new Iphone 8 and its new wireless charger will be shown.
By using µCT technology, we are now able to provide new way of analysing an underperforming battery by considering different issues within one set of data. Destructive technics would only allow you one "guess" per analysis, µCT would allow you to express few hypothesis and then validate them by looking at the internal microstructure structure; creating a more efficient way of pin pointing defects.



Samsung Galaxy 7 delamination battery



Iphone 8 – Battery highlighted



Wireless charger (Iphone 8) – charging coil highlighted

17

Quantifying Intracortical Bone Microstructure In Birds: An Assessment of Two-Dimensional And Three-Dimensional Methods for Characterising Bone Histology

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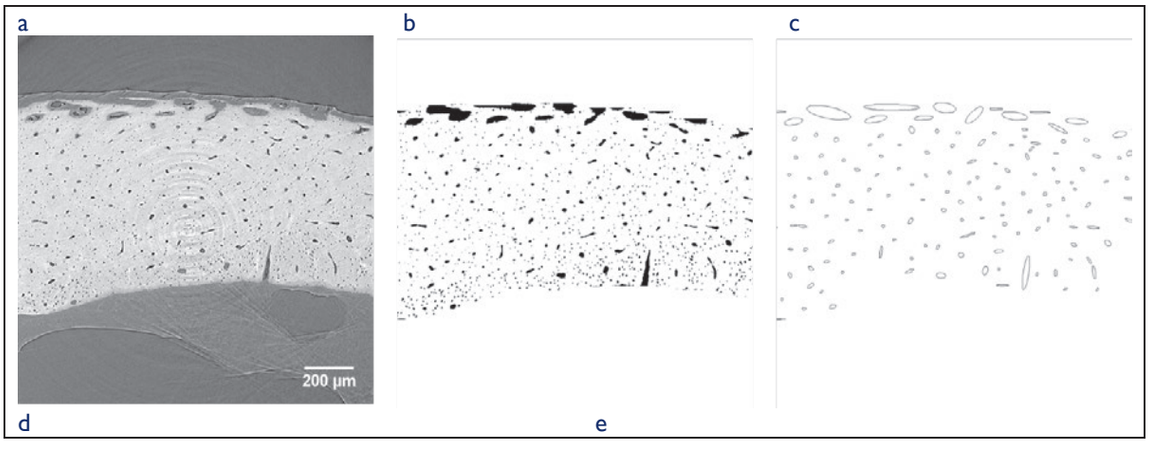
Characterising intracortical vascular canal density and orientation, as well as shape, size and density of osteocyte lacunae in fossil bone is important in understanding the growth, life and death of extinct animals. In palaeobiology, bone histological parameters are usually measured from thin sections, an essentially two-dimensional (2D) approach, so shape and orientation of relevant structures are inferred from fitting idealised three-dimensional (3D) geometries to 2D cross sections. Canals are modelled as perfect cylinders, and osteocyte lacunae as ellipsoids, some methods assuming a longitudinal orientation. As 2D methods rely on conformation to strict geometric assumptions, 3D methods have been proposed but the accuracy and sensitivity of these methods in comparison to their 2D counterparts, outside underlying geometrical assumptions, has not been examined.
In this study, we generated populations of 100 randomly rotated 3D cylinders (canals) for cross sectional aspect ratios of 1:1, 1:1.25, 1:1.5, and 1:3, 100 randomly oriented ellipsoids (osteocyte lacunae), and 100 longitudinally oriented ellipsoids (rotated 0-22.5° from the major axis). In 2D, we fitted ellipses to cross sections (Figure 1.a-c) to measure cylinder orientation, (defined by a longitudinal and radial angle), and ellipsoid shape and volume. In 3D, we skeletonised canals to calculate orientations (Figure 1.d-e), and fitted ellipsoids to the osteocyte lacunae. We compared results to the values input to generate the models. For six samples of duck cortical bone assessed by synchrotron-based computed tomography (1.6 µm voxel size, imaged at I13-2 beamline, Diamond Light Source) we calculated the same morphometric measures, alongside lacunar density and bone volume fraction (BV/TV).
For cylinders, a slight skew (1:1.25) in aspect ratio resulted in a reduced correlation between predicted and 2D-based results for the radial angle (1:1, r^2=0.986, 1:1.25, r^2=0.613), and a 6.1° underestimation of the longitudinal angle. For 3D measurements, r^2 was close to 1 for all aspect ratios. In real datasets, 2D and 3D measurements of canal orientation, and osteocyte lacunar volume were not correlated, though BV/TV and osteocyte lacunar density were (r^2=0.8995 and 0.8919 respectively).
These results highlight the importance of using appropriate 3D imaging and 3D quantification for characterising shape and orientation of cylindrical structures such as the intracortical canal network.



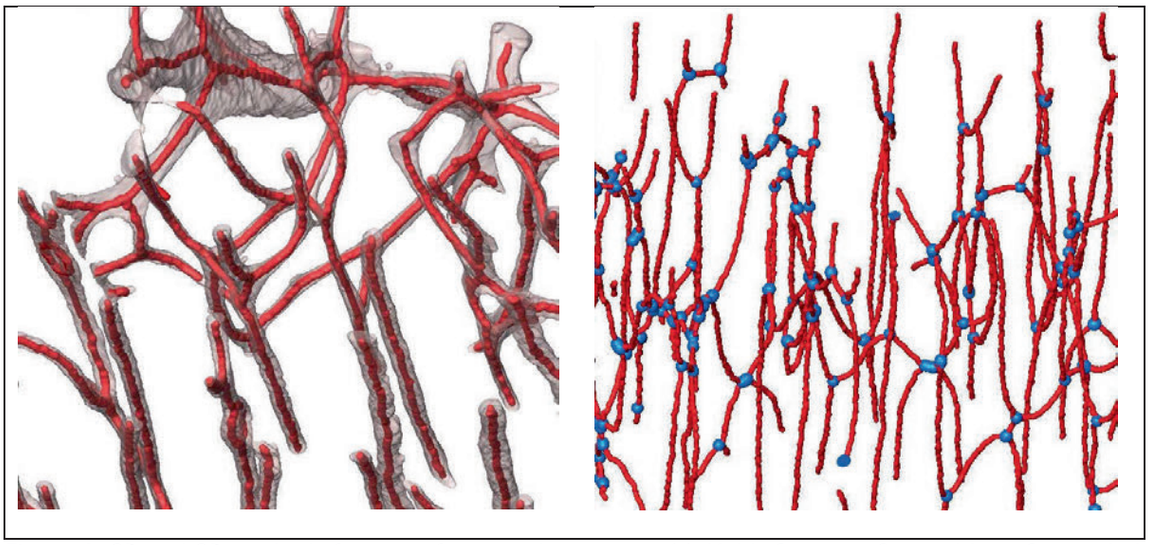


Figure 1: *2D and 3D* methods for quantifying *canal orientation. (a) Midshaft region of cortical bone from a duck tibiotarsus (1.6um voxel size, imaged at 113-2 beamline, Diamond Light Source). (b) Intracortical porosity segmented using a greyscale threshold and cortical mask. (c) Best-fit 2D ellipses for canals, separated from osteocyte lacunae by area.* (d-e) *3D* characterisation *of* the *canal network*, including (b) *skeletonisation: original segmented canals (transparent) are thinned to a single line of voxels (red, dilated for visualisation purposes)* and *(c) analysing the skeleton: locations of branch points (blue), length of branch and Euclidian distance between nodes are recorded. Visualisation in Avizo.*

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Image Optimisation in Micro Computed Tomography for Feline Hearts

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Keywords: *Micro Computed Tomography, Cardiac tissue, Tissue preparation, Optimisation, Feline*

Micro Computed Tomography (Micro CT) allows high resolution imaging using multidetector X-ray source to give 3D imaging reconstruction of tiny objects at micron resolution. We have recently published detailed micro CT imaging in a variety of different settings, including craniopharyngioma phenotyping (Apps JR et al., 2016) and fetal organ imaging. (Hutchinson JC et al., 2016).

In order to image human surgical specimens or fetal organs as part of a post mortem assessment, iodine is used to enhance soft tissue contrast for diagnostic purposes. This study empirically assessed the iodination optimisation protocol to allow high tissue contrast in feline cardiac samples, which would allow the protocol to be transferred to human samples.

We present the preliminary results from feline cardiac tissue preparation optimisation where signal intensity, and depth of tissue penetration were quantitatively assessed.

This is a sub-study as part of a larger trial in collaboration with the Royal Veterinary College into an animal model of hypertrophic cardiomyopathy, and has implications for the study of this disease in humans.

References:

Apps JR et al., Imaging Invasion: Micro-CT imaging of adamantinomatous craniopharyngioma highlights cell type specific spatial relationships of tissue invasion. Acta Neuropathological Communications. (2016) Jun 3;4(1):57.

Hutchinson JCH et al., Virtual pathological examination of the human fetal kidney using micro-CT. Ultrasound Obstetrics Gynaecology. (2016) Nov;48(5):663-665.

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Bioinspired Lightweight Vehicle Design Through Advanced Correlative Microscopy

Nicola Thomas[1], Caroline Buttler[2], Richard Bevins[2], Will Harrison[1], Ria L Mitchell[1], Peter Davies[1] Richard E Johnston[1]

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[2.] Department of Natural Sciences, Amgueddfa Cymru -National Museum Wales, Cathays Park, Cardiff

***Keywords**: Bioinspiration, Structures, Lightweight, Correlative, microscopy, X-ray microtomography, Bioprospecting*

Natural selection and evolution have shaped and moulded biological structures over millions of years, resulting in diverse and intricate forms, ranging from stronger beaks to crack tougher nuts, to lighter bones to help birds fly. The study of these biological architectures can provide insight, not only to biologists, but also to design engineers, and architects. Bioinspiration involves looking to nature to find ways of optimising design, and has been implemented in a wide range of uses, for example, enhanced strength in vehicle and aeroplane components using honeycomb structures inspired by bee hives, or swimsuits that mimic the hydrodynamic shark skin for reducing drag in water. These architectural designs are of great interest to materials scientists, being formed in ambient conditions, with limited resources in a specific environment, yet have properties that often exceed those of human-made materials.

Working within the Advanced Imaging of Materials (AIM) Facility, and in collaboration with National Museum Wales, this project is undertaking 'bioprospecting' of museum specimens to investigate biological architectures as a tool to develop bioinspired lightweight structures for the aerospace, automotive, design, and other advanced manufacturing sectors. By studying mineralised biomaterials and considering their form and function, we hope to establish how these features may be adapted for potential engineering applications that benefit society, primarily as a means for reducing greenhouse gas emissions. Lightweight samples are investigated using X-ray microtomography (μCT) and scanning electron microscopy (SEM). Areas of architectural interest are segmented using various 3D visualisation software packages, to reproduce their structure, or a modification of, via 3D printing. Mechanical testing is also conducted to ascertain structural and material behaviour to both understand the natural structural performance and for potential real-world uses. This rapidly developing area of research, where biological form is used to inspire design strategies for engineering structures, is extremely exciting and the diversity and expanse of nature is an almost unlimited resource for a bioinspired future.

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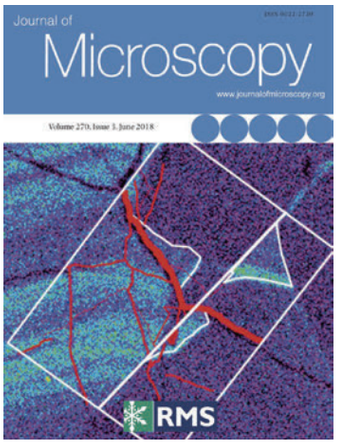

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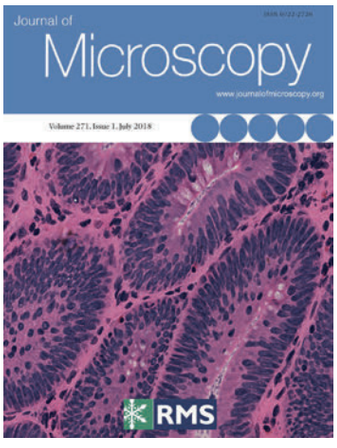

Recent Articles of Interest

- Quantitative 3D comparison of biofilm imaged by X-ray micro-tomography and two-photon laser scanning microscopy
- Comparative performance assessment of beam hardening correction algorithms applied on simulated data sets
- High-resolution x-ray tomographic morphological characterisation of electrospun nanofibrous bundles for tendon and ligament regeneration and replacement
- Pore space extraction and characterization of sack paper using μ-CT
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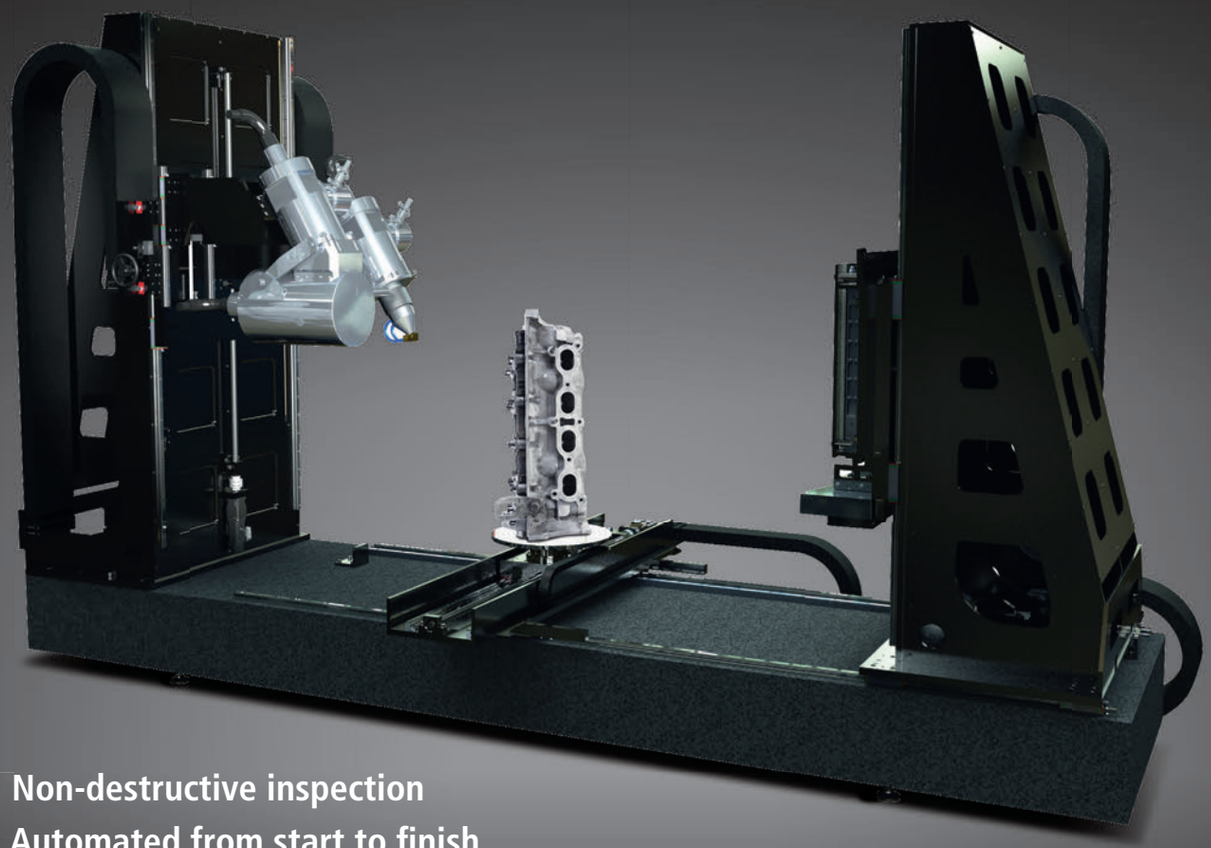

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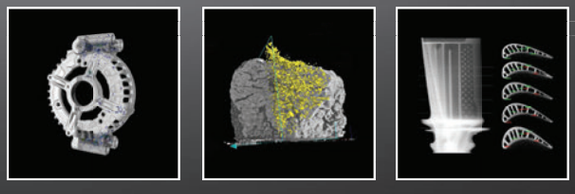

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Imaging Competition

Thank you to those who entered the ToScA Imaging Competition. The images will be on display throughout the symposium and the winners will be announced at the Symposium Banquet at Warwick Castle.

A Cog in the Machine

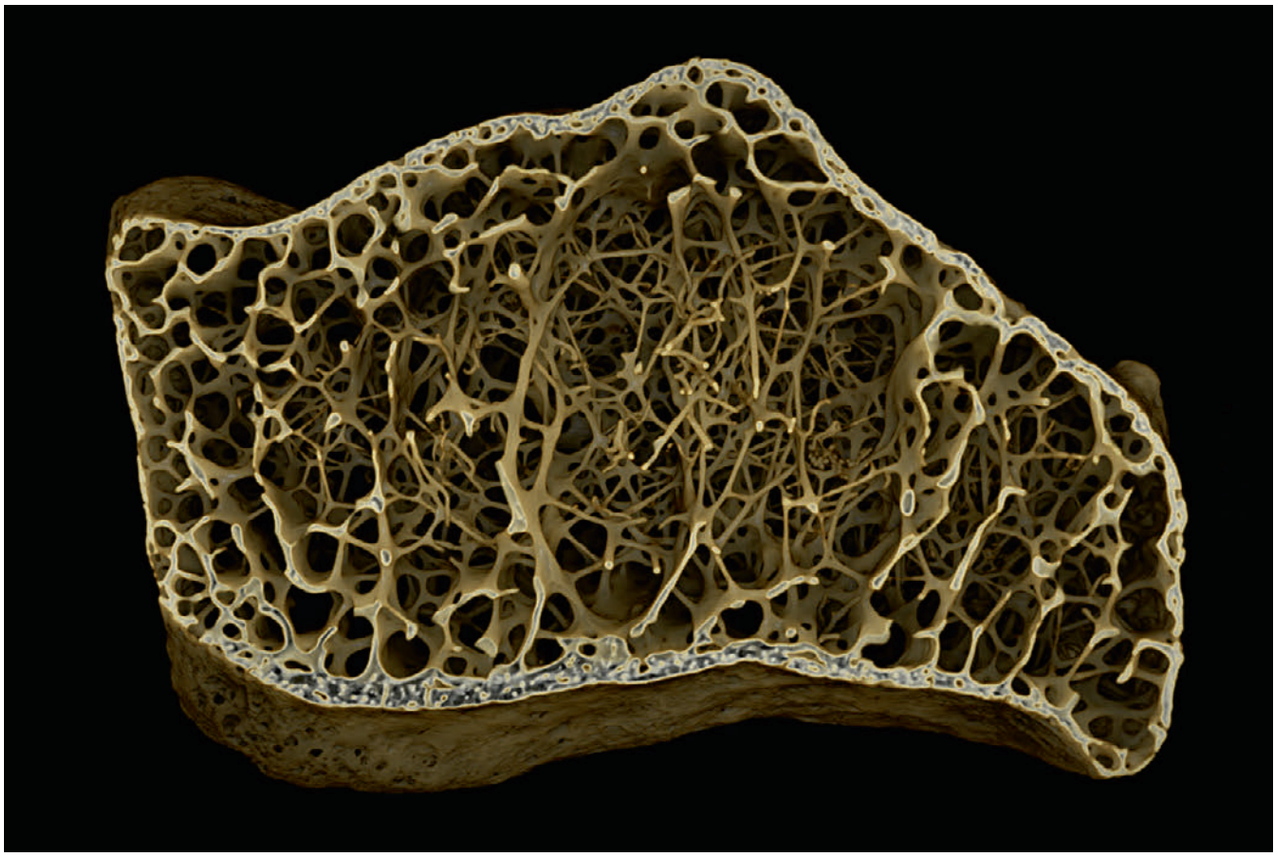
A single projection of a Prague Old Timer pocket watch provides a unique and beautiful insight into the intricate design and build of this machine.

Sarah Aldridge, Swansea University

Method in the Madness

This slice through of a human distal radius (or wrist bone) appears to be a tangled web of trabecular bone. But in reality this tissue is under constant redesign, carefully dispersing to provide support in areas that need it most, and distribute forces across a much larger area to prevent breakages.

Sarah Aldridge, Swansea University



CLAMping to a Surface

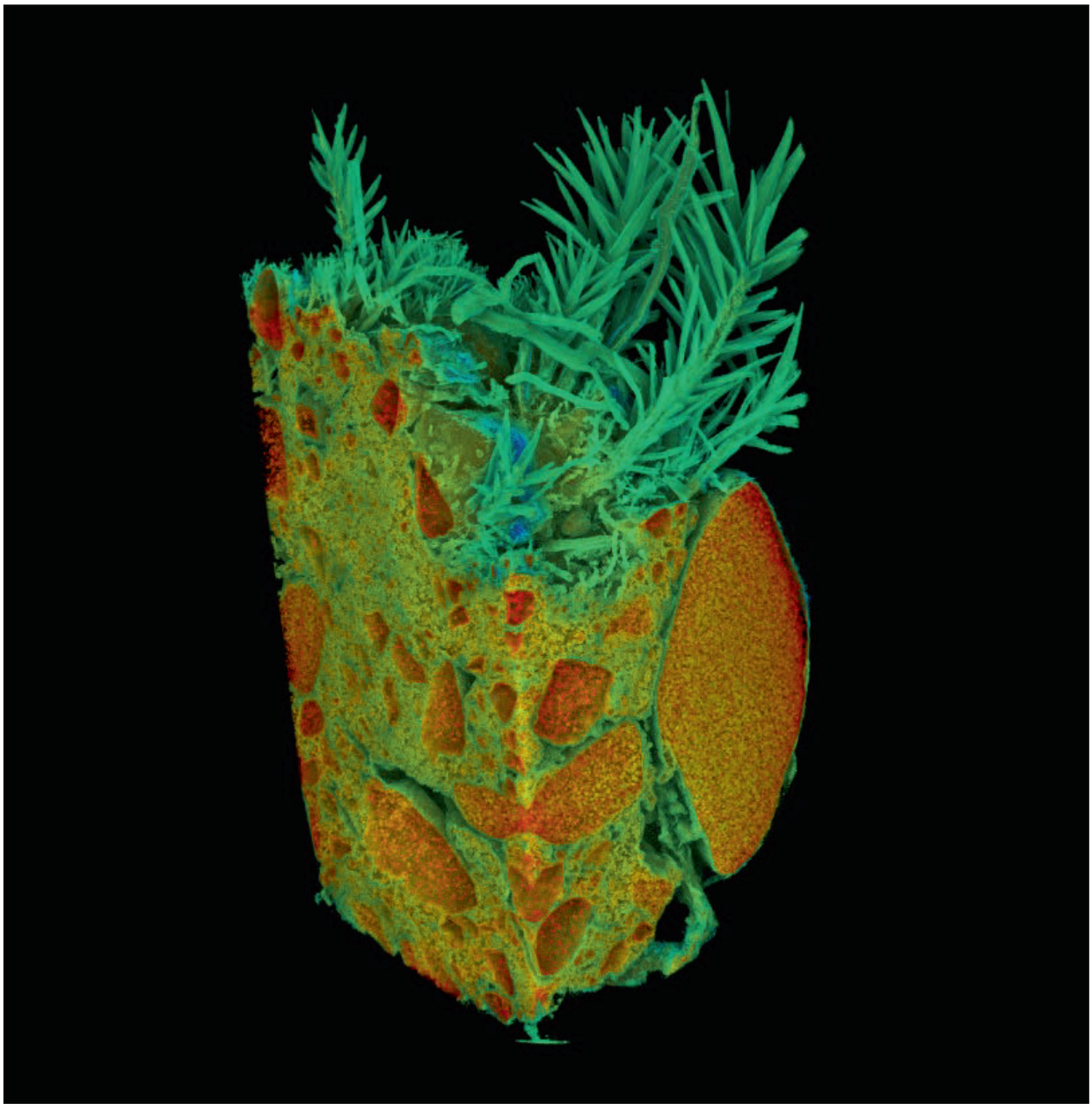
Nature is fascinating, and so much can be learned from simply picking up a shell off the beach. This X-ray CT image depicts a Pecten marine bivalve shell (note distinctive ribs radiating along the shell surface), common on beaches surrounding south Wales, which has become encrusted with bio-precipitated calcareous tubes of marine polychaete worms. In places these are filled with beach sediment, which shows up as higher density red colour. In addition, there are colonies of bryozoa which form intricate honeycomb-like networks over the surface of the shell, utilising the shell as a growth substrate. This example highlights just some of the intricate micro-interactions that occur in the marine realm, and that by looking closely at beach debris it is possible to re-tell a story of colonisation, different life strategies, and adaptability.

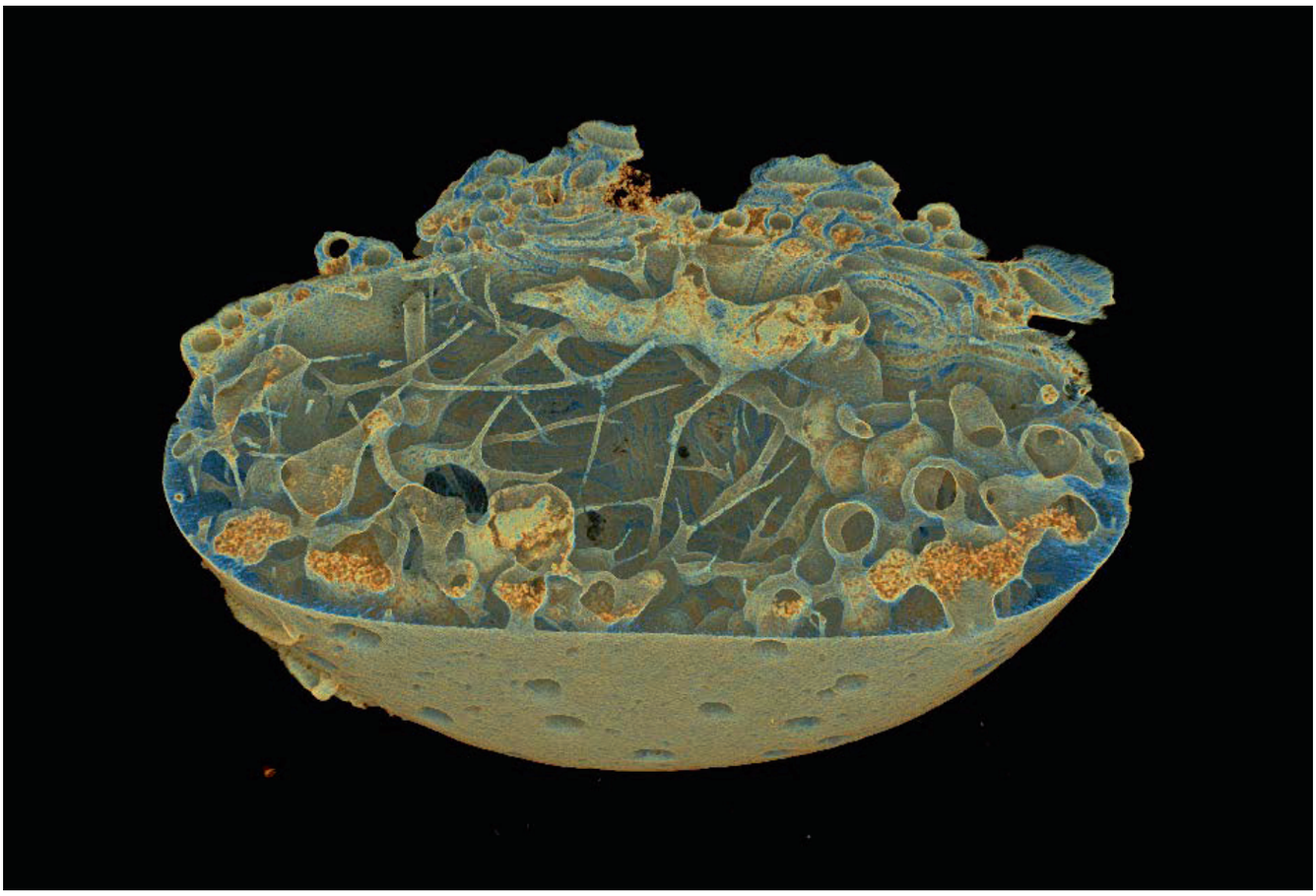
Dr Ria Mitchell, AIM Facility, Swansea University

Moss Forest

This image depicts a ~3 cm long soil core through a cryptogamic ground cover (CGC); this particular example is dominated by the moss Polytrichum juniperinum. Different densities of material within the soil show up as different colours; the high-density clasts are represented by red, the soil matrix by yellow, and the organic component shown as green. On this scale the moss looks like a forest, even though the moss is only ~8mm tall.

Dr Ria L Mitchell, AIM Facility, Swansea University





Nature's Underground

There is more going on within a simple beach pebble than you might think. By stripping away a surface via X-ray CT scanning, we have revealed complex networks of tunnels and caverns hidden away from initial observations caused by burrowing and boring polychaete worms. This intricate network is reminiscent of the London Underground – complex tubes, caverns and tunnels of varying sizes enabling the worms to go about their business.

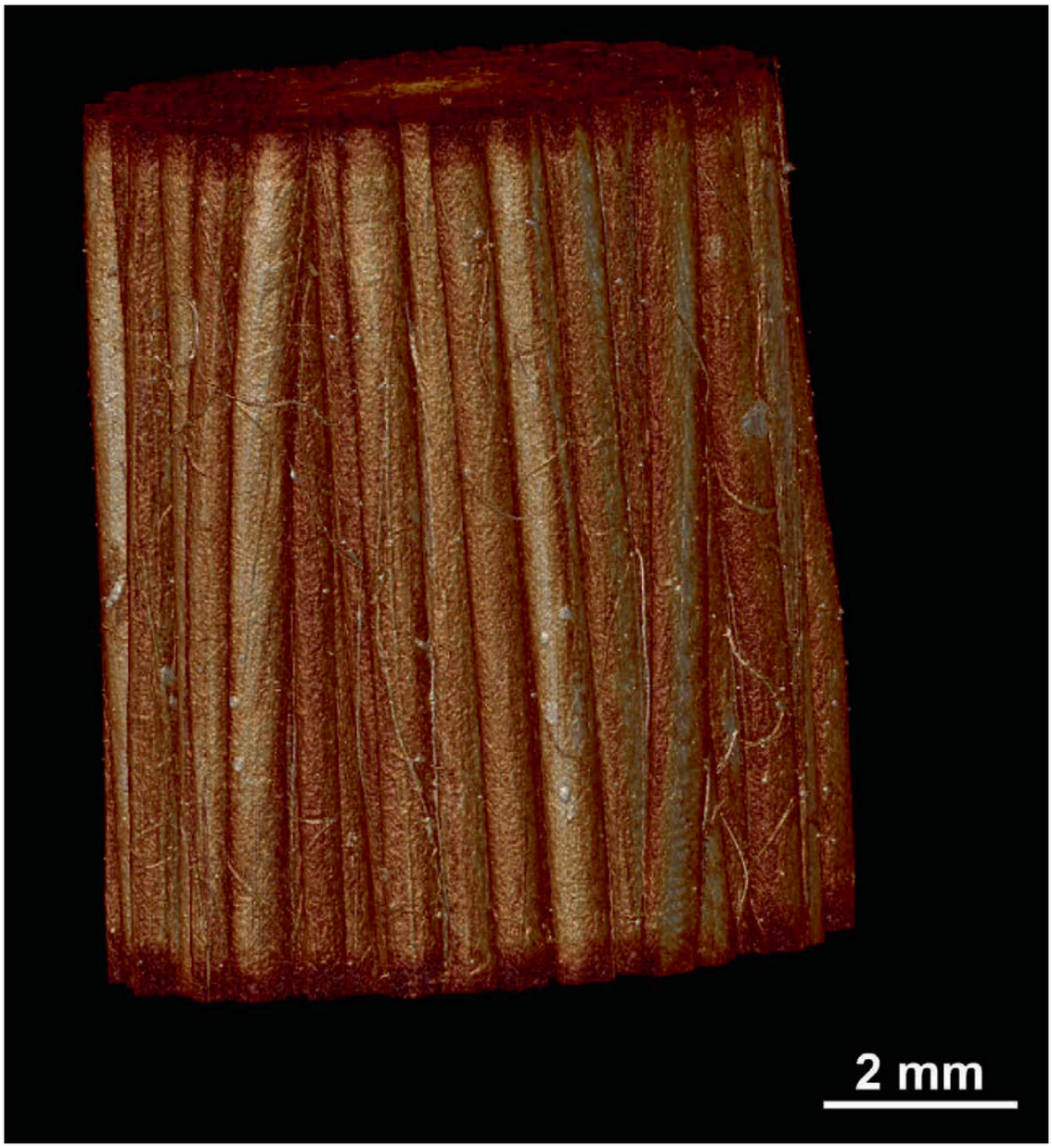
Dr Ria Mitchell, AIM Facility, Swansea University

T4H: Tendons for Humans

High-resolution x-ray tomography (XCT) image of a hierarchical multiscale electrospun scaffold for tendon tissue regeneration (diameter = 7.5 mm), made by 100 bundles of nanofibers (diameter = 550 □m) Nylon6.6. The nanofibers (diameter = 200 nm) are axially aligned with the bundles. The scaffold perfectly replicates the hierarchical structure of a human tendon: from the fibrils of collagen, passing to the fascicles, and finally replicating the complete tendon. The scaffold replicate also the epitenon, thanks to a random nanofibrous sheath (random nanofibers on the surface of the hierarchical multiscale scaffold).

Many thanks to the Alma Mater Studiorum - Università di Bologna for the production of the scaffold, and the Zeiss Global Centre of the University of Portsmouth for the use of the high-resolution x-ray tomography.

Alberto Sensini, Università di Bologna and Gianluca Tozzi, University of Portsmouth



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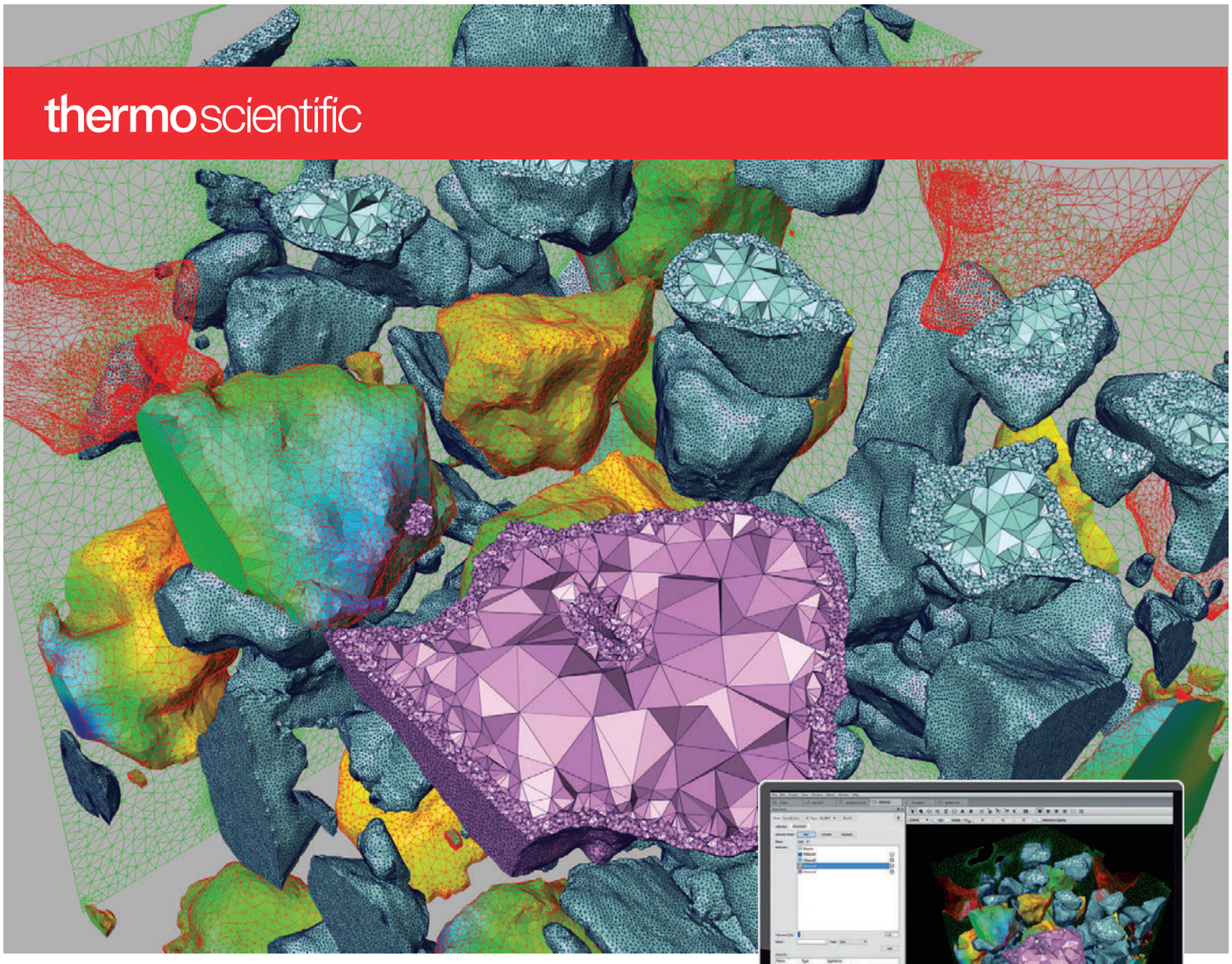

Data courtesy of Visible Cement Dataset

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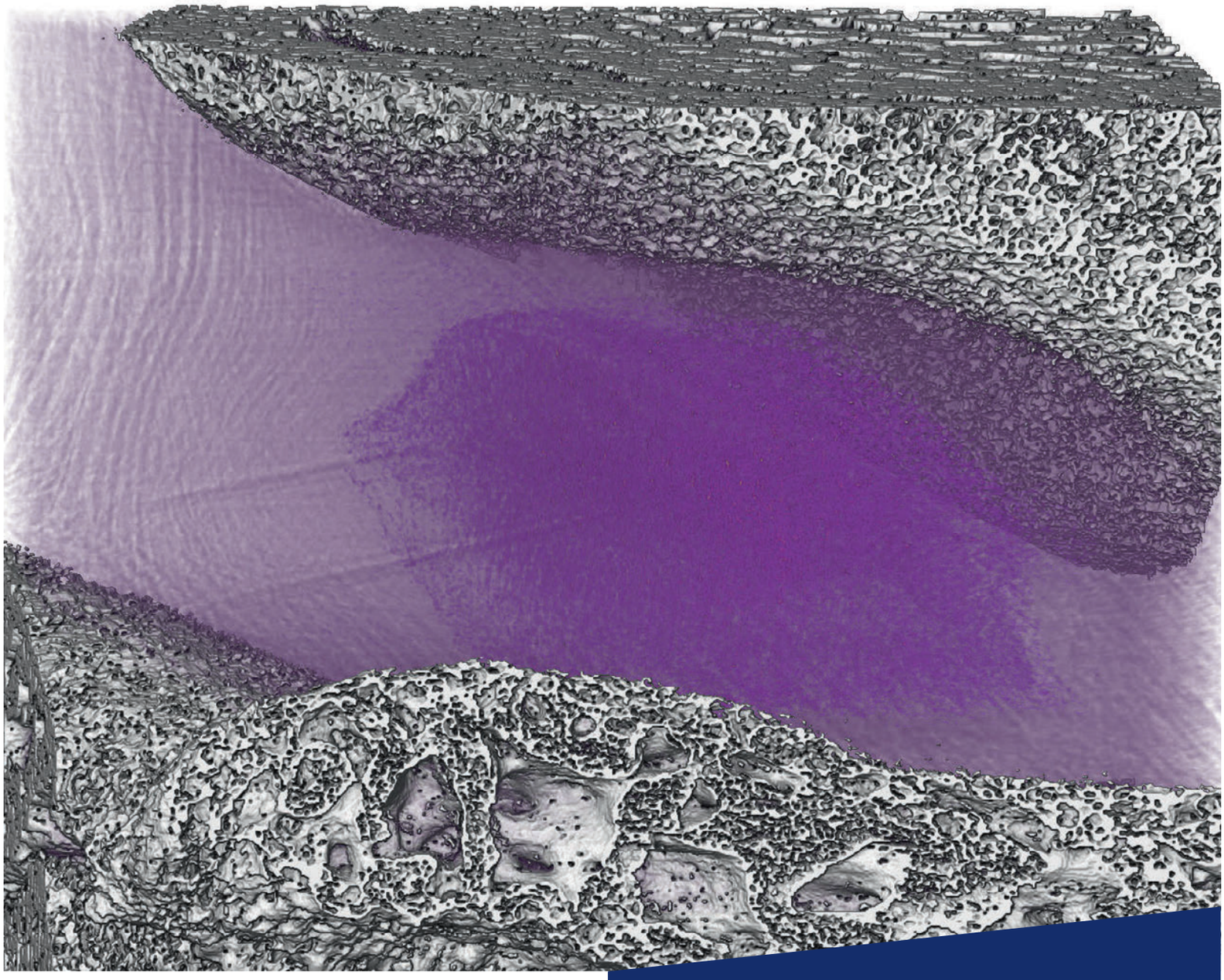

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