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EPSRC X-Ray Tomography Roadmap 2018

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With thanks to the Panel of Expert Readers

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Summary

The UK has a long track record with X-ray computed tomography (CT), spanning back to the development of CT for medical applications, leading to Hounsfield's Nobel Prize for medicine in 1972, and a decade later, the development of CT for materials applications by Elliot & Dover.

In recent years, X-ray CT has emerged as a key technique for materials characterisation, and is widely represented across the EPSRC portfolio: the activity supported is much more than just capital investment and includes an extensive track record of technique development, which is also echoed at Diamond Light Source, providing next generation modalities for X-ray imaging for the wider community, and at ISIS providing complementary neutron tomography options. We estimate there are now ~100 X-ray micro CT systems in the UK and the growth of industrial CT is predicted to follow similar projections to Medical CT market which is expected to triple over the next 5 years.

This proliferation of this technology is underpinned by sustained investment in technique, hardware and algorithm development, which has established the UK as a leading centre for X-ray CT, with extensive lab and synchrotron infrastructure and a large and proactive user and developer community. To retain this position, the UK should consolidate its activity: this would enable new users to embrace tomography techniques, and support developers to drive the next generation of techniques.

In September 2017, we launched the EPRSC Roadmap in X-ray Computed Tomography, which builds on previous surveys from CCPi/Manchester and the National Physical Laboratory (NPL).

The roadmap aims to address:

- What is the current state of the X-ray CT landscape in the UK?
- What is the science we need to do and what are the tools we need to do it?
- What technical developments are required, and where should we focus our developments to remain world leading?

The timeline of activities is as follows:

- Summer 2017: Formation of Steering Committee
- September 2017: Major Survey of X-ray CT Users (>130 respondents)
- November 2017: follow up interviews with facility managers
- November – December 2017: Town Hall Meetings in London and Manchester (> 100 attendees in total)
- December 2017: Follow on survey, focussed on industry users (>110 respondents), aimed at capturing those who were unable to respond to major survey
- 2018: Data analysis, roadmap formulation and expert readership

The outcome of the process is a 'living document' for the user and developer community to guide the development of X-ray CT techniques, and their applications.

Scope: X-ray CT is one modality in a portfolio of tomography techniques which range from process tomography to electron and neutron imaging. Each modality contributes substantially to scientific and

engineering research in the UK and its translation to industry, and the UK has led the development of many of these fields.

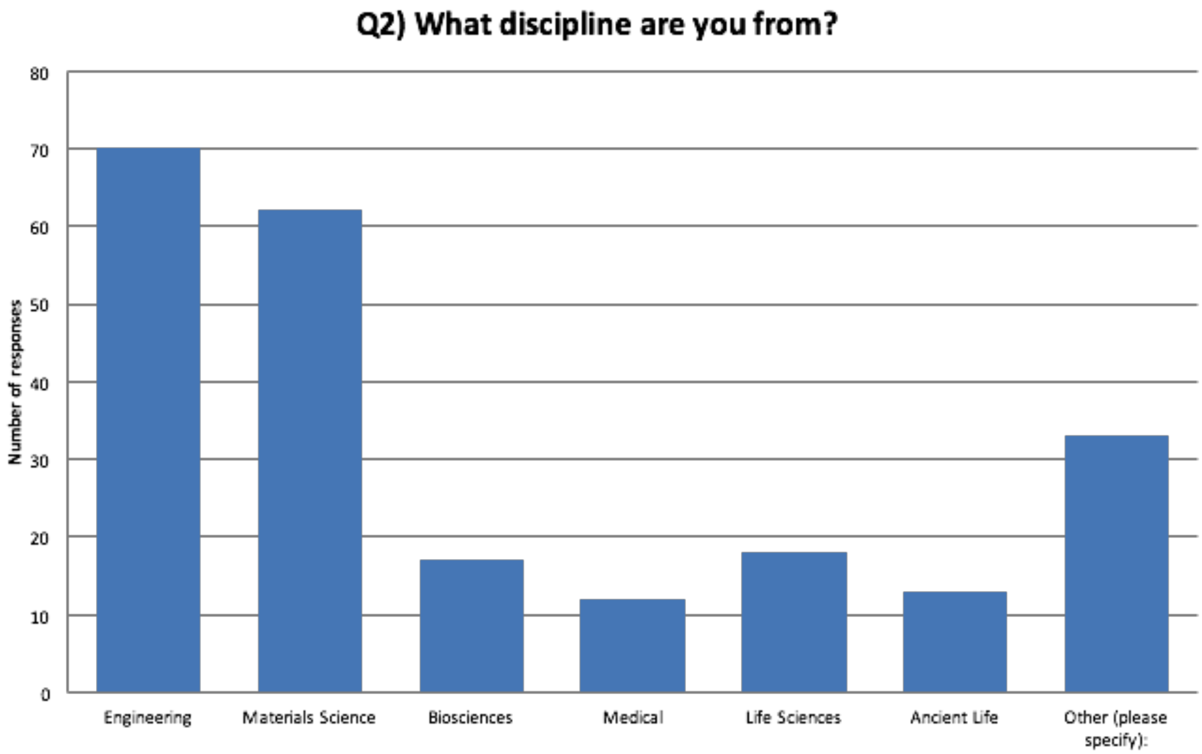
The steering committee, in consultation with the community has identified the roadmap as focussing on X-ray CT, this is not intended to overlook the significance of other modalities; indeed the complementarities of a correlative tomography approach is widely acknowledged. However, the committee unanimously decided that whilst there is some overlap in algorithm development, and isolated examples of overlap in application, the fundamental differences in hardware and technique were not reconcilable. Moreover the roadmap seeks to focus solely on X-rays so as not become unwieldy or disperse in its scope. As this activity is seeded by the EPSRC, applications of medical CT are not considered.

<u>User Survey</u>

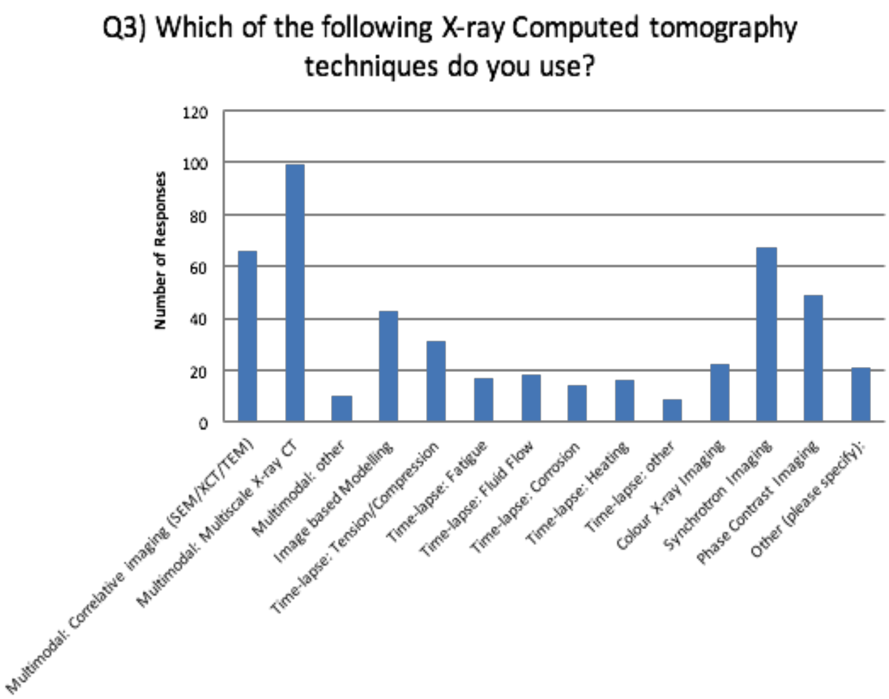
"This survey serves to remind us of the UK's wide and vibrant range of research into tomography itself and its leading-edge applications in science and engineering - indeed, research into tomography itself has brought at least two Nobel prizes to the UK: Sir Godfrey Hounsfield (1979) for X-ray CT, and Sir Peter Mansfield (2003) for MRI" Quote from Survey Respondent

Launched in September, the user survey attracted more than 140 respondents from a cross section of backgrounds and with a good geographical spread within the UK. > 100 respondents were university based, with ca. 20 from industry and the remainder from national labs and museums.

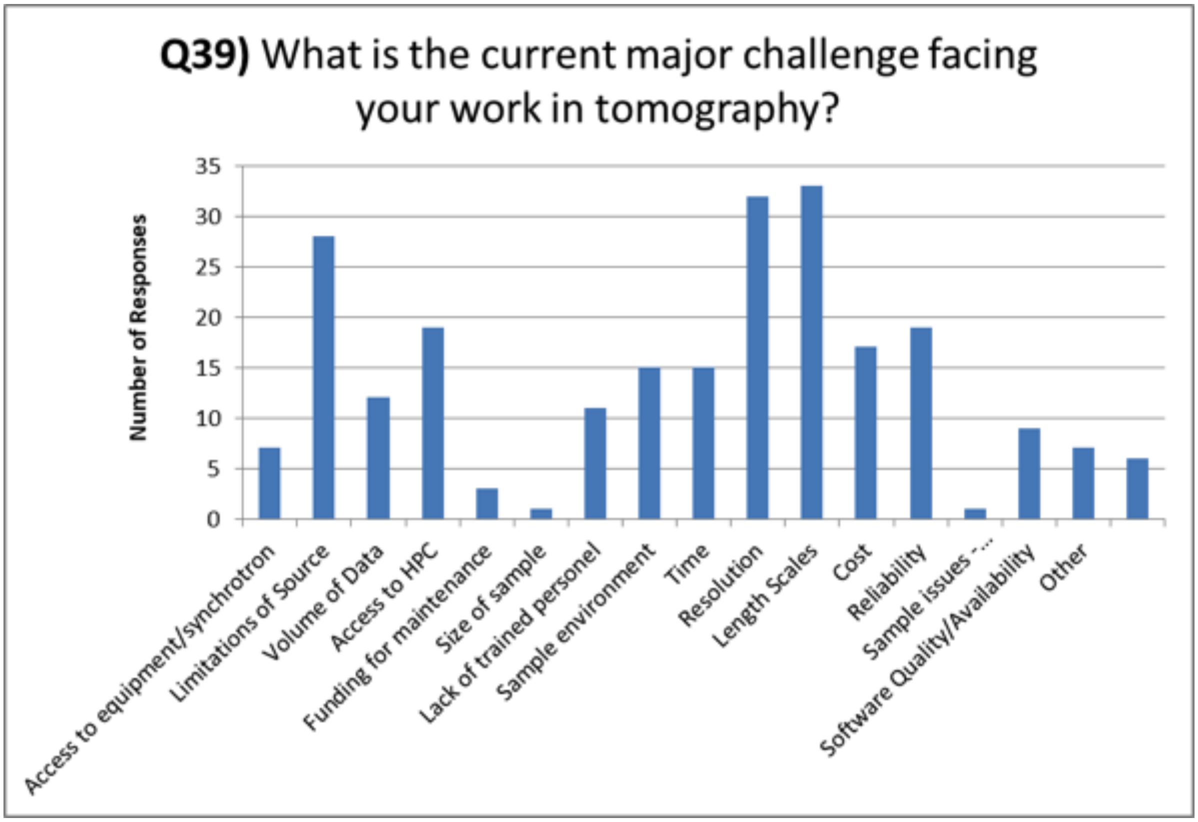
The discipline spread is shown below, with the largest return from the engineering and materials science communities.



Around one third of respondents owned at least one X-ray CT instrument, the majority of which had been purchased in the last 5 years, predominantly funded by EPSRC and/or universities. Although around 35 respondents offered instruments as part of a user facility, there remains significant demand for access (with various requirements for reduced cost and improved geographical spread) indicating a substantial demand and capacity for further infrastructure investment.



In addition to absorption contrast CT, users have experience with a range of ‘advanced’ imaging techniques including multi-scale, phase contrast and colour imaging, as well as correlative microscopy. Just under a half of users undertake in-situ or operando tomography which indicates a rapid adoption of these techniques (this includes heating/cooling, deformation, flow, indentation and electrochemistry). Whilst this survey predominantly focused on laboratory capabilities, a large number of respondents also use synchrotron techniques, identifying the complementarity of local and large scale facilities.

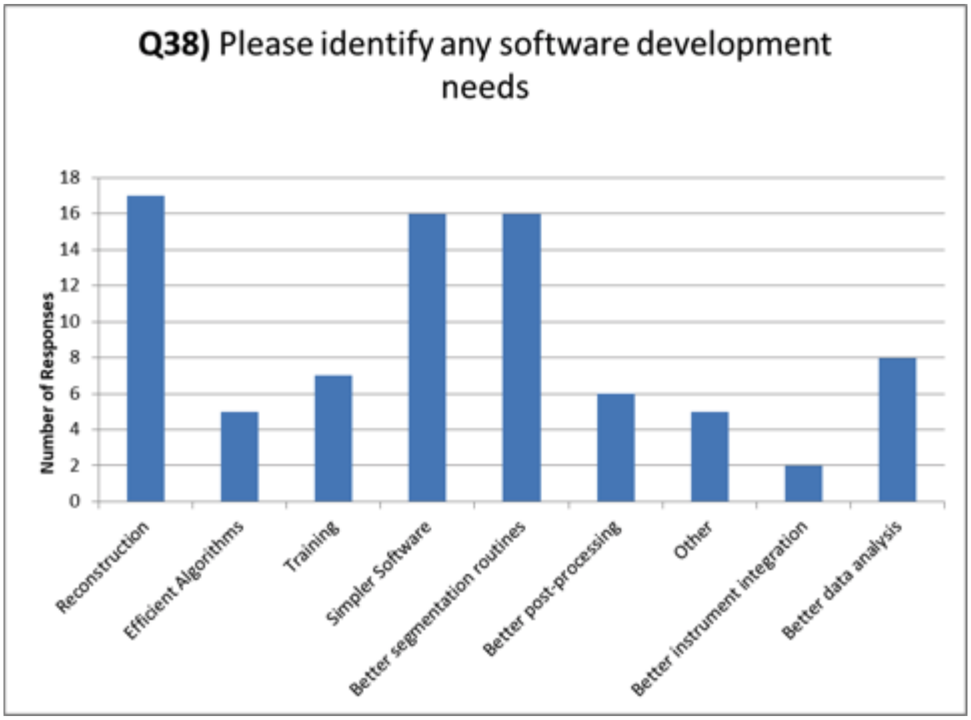


Users were asked what major technical challenges they faced in completing their research; as the survey attracted respondents from a breadth of discipline, the following common themes have been identified:

- Application of demanding environments (heating, cooling, corrosion, live animals, tension/compression, electrochemistry etc)
- Imaging large samples at high resolution
- Improving temporal resolution for dynamic scans
- Reducing dose for radiation sensitive samples
- Challenging materials (near density, high or low Z)
- Coupling imaging with spectroscopy for chemical analysis
- Nano-scale imaging in real time
- Integration of X-ray CT with modelling tools
- Poorly defined resolution standards and benchmark data sets for metrology purposes.

Users also identified challenges with access (cost, availability, geography) and a poor understanding of the availability of instrumentation and software, as well as challenges with data handling and archiving.

Users adopt a broad range of software for image analysis and have experience of developing their own software. By contrast most rely on commercially available reconstruction algorithms.



A range of software development needs were identified, in particular relating to:

- Image segmentation, (and the application of machine learning)
- Reconstruction methods artefact minimisation
- Tools for data handling and archiving
- GPU coding and methods for compute speed improvements
- Software environments enabling correlation across modalities

In addition to these technical challenges, issues associated with cost of commercial licenses, ease of use of open source software and appropriate training provision were also identified.

Users were asked to identify technical developments that would aid their research, these included:

- High brilliance sources for faster scans
- Phase contrast imaging (in particular in laboratory environments)
- New reconstruction algorithms (e.g. iterative)
- High energy scanners (for large and dense samples)
- Coupling with chemical or crystallographic analysis
- Integration of image analysis and improving speed of analysis
- Automation of processes for data collection/reconstruction/analysis as a ‘tomography pipeline’
- Larger samples, at highest resolution

A recurrent theme is the translation of capabilities typically associated with synchrotron facilities to lab environments (colour imaging, spectroscopy, phase, crystallography).

The survey highlighted needs for improved training to build a community of tomography users and experts, these included suggestions outlined below:

- Training in image analysis and reconstruction, in particular for open source software
- Hands on training (for hardware)
- Masterclasses specific to technique or research domain
- Thematic webinars and wikis for remote access
- Communal data available for training
- Forums to share best practice

A number of respondents noted that training provision was already serviced by networks including the Combined Computational Project for Imaging (CCPi), Tomography for Scientific Advancement (TOSCA) and Dimensional X-ray Computed Tomography (DXCT) amongst others. Funding to sustain access to these courses was deemed as essential.

Additional, selected responses from the survey are quoted below, reflecting the X-ray tomography zeitgeist at the time of the survey:

Originally for example [users] were happy with 3D imaging but are increasingly looking towards time base imaging.

Synchrotrons are great and get round this but access is difficult, sporadic and costly …. and so much can be done at advanced lab scale (mid range) facilities.

Many experiments are limited by the in situ rigs available and some sharing of rigs across the community in lab and synchrotron facilities would be beneficial.

We are … constantly in need of good quality staff to help push back the boundaries of this science.

For a National Research Facility (also known as Mid Range Facility!) to work... there needs to be the ability to work in an interdisciplinary way...guidance and collaboration are key.

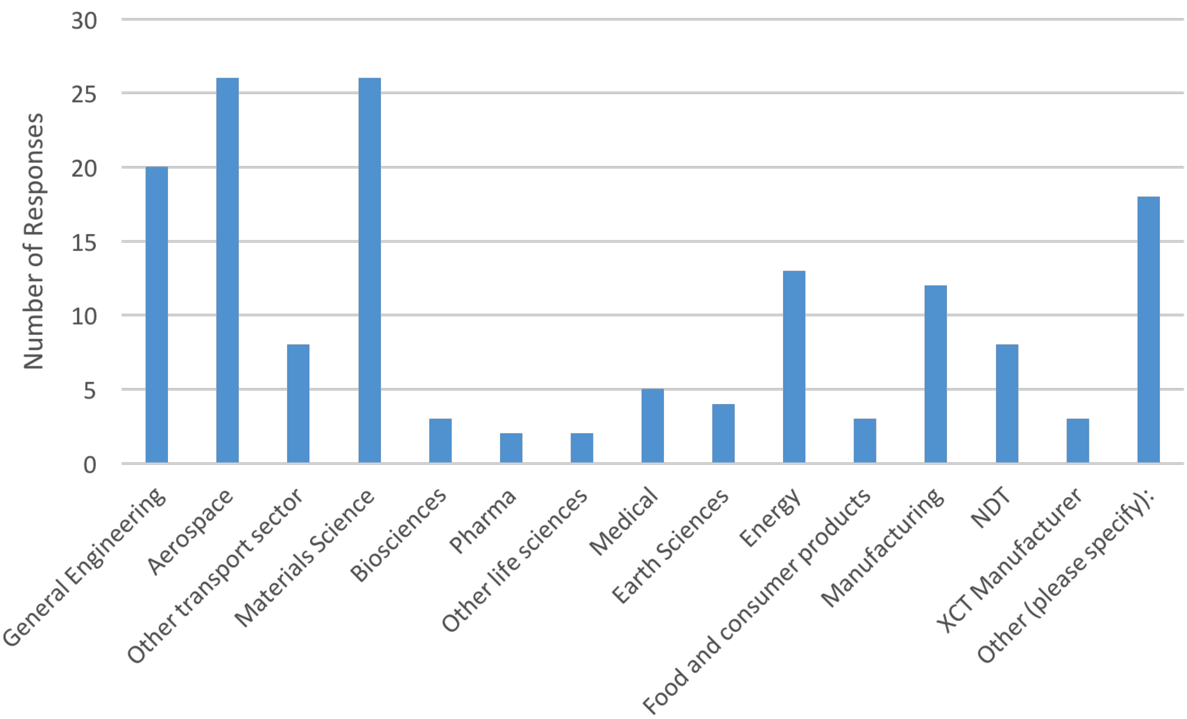
Many people want to use X-ray Imaging but struggle to afford the access costs and/or do not have the skills to analyze the data that come with it. X-ray is not yet ubiquitous like SEM and these are a couple of major obstacles to further uptake.

It is also clear that quantification for Industry is of great importance, further education is required to give confidence but so are proper protocols and standards for quantification of the data

Improved access is essential for broader application

Industry Survey

Following feedback from the London town hall meeting, a more focused survey, targeting industry users was launched, and attracted ca. 72 respondents, across a broad range of sectors



The survey focused on:

- Which industries/sectors are showing significant uptake of X-ray CT facilities.
- How and where do they access X-ray CT facilities.
- Core capability needs/priorities (sample dimensions, resolution, time series analysis *etc.*).
- Challenges and future needs.

To encourage uptake in the commercial community, the questionnaire was brief (15 questions, see appendix), and mostly multiple choice, but with free-text boxes to expand on default options as required.

72 industrial survey responses were received: 14 areas of interest were identified, including engineering, life sciences and earth sciences, although engineering and associated sub-disciplines clearly dominated. The five most highly represented were: Aerospace (26), Materials (26), General Engineering (20), Energy (13) and Manufacturing (12).

The survey conducted by The National Physical Laboratory in 2015 indicated that medical/clinical is a further major application of X-ray CT. As there are well-established business models and stakeholders (research community, equipment suppliers, funders, users, operators, standards, training provision *etc.*) this was considered out of scope.

Within the current survey, 1/3 of industrial responses identified as operating their own X-ray CT capabilities, whilst the majority (2/3) access machines externally. Of the machines owned by industry, many run to relatively moderate energies (225 kV), but a significant number (~20%) used high energy systems (400 kV+ to MeV range) and various written comments were made regarding the need to address larger and denser samples, indicating what may benefit UK industry in the future.

Of those companies using external machines, 84% were accessing university facilities, 14% used X-ray CT manufacturers' sites, along with a limited number accessing Catapult Centres (2%). Some companies accessed both commercial and university facilities. As such, it is evident that university X-ray CT facilities currently play a significant role in terms of providing industrial measurement services.

There is evidence of scope to improve capacity in service provision, with the majority of service requests (51% of responses) reporting a delivery time of more than 1 week. 37% of all service requests were delivered by providers within 1 week, whilst more than 20% of responses experienced a delivery time of between 1-6 months. It is also highlighted from the survey that more than 20% of responses report cost and delivery time as major challenges when accessing X-ray CT facilities.

In terms of fundamental system requirements, 17% of responses have samples with sizes of less than a millimetre, about 48% responses have samples between millimetre to 10 cm and approximately 35% responses have samples in large scales (greater than 10 cm and up to several metres). Around 60% of responses indicate measurement tasks at resolutions between 1-100 µm, 20% required sub-micrometer level resolution, whilst the remained indicate sufficient resolution in excess of 100 µm.

A minor but non-trivial number of responses (27%) use in situ or operando tomography for time series/through-process analysis, dominated by thermal and mechanical studies (~70%), along with behaviour in fluid environments (20%).

Industry users identified a wide range of challenges in contemporary X-ray CT use, with 41% of responses highlighting basic technical aspects such as sample size limits, spatial resolution and scan throughput, and 22% of responses highlighting supporting capabilities, such as training, data processing and system calibration.

Regarding future developments of X-ray CT, the improvement of technology (resolution, larger measurement volume, faster scan speed) accounted for 45% of total responses, the quality of scan (accuracy and error reduction) accounted for 28%, with flexibility of scan and automation/robotics accounting for 11%, and improvement in software for 9%. Of the free-text responses, many (8 of the 14 entered) highlight a need to improve capabilities of large and/or strongly attenuating samples.

Town Hall Meetings

Two town hall meetings were held in London and Manchester in late 2017 to present preliminary data from the survey and to conduct a deeper dive on capability and capacity, and future needs as well as identifying possible science highlights from the UK's catalogue of tomography research.

Manchester Town Hall Meeting – December 2017

The Town Hall meetings held in London and Manchester focused on:

1. Identifying gaps not covered in the online survey
2. Identifying historic and predicted impacts from the X-ray tomography community
3. Identifying future needs for X-ray tomography in the UK

Identifying Gaps

Attendees generally felt that the survey had captured hardware and software infrastructure and requirements relatively well – suggestions and discussions related to capability and capacity included:

- Monitoring access, usage etc. (what is done where? who is doing it?)
- Providing a databases of facilities (including kit, software, in situ, costs)
- Data storage and network issues
- Need for more in situ capability
- Matchmaking needed between users and facilities
- Emphasis that capability is not just hardware; also experts, new trainees/students/support roles.

Attendees agreed that shared knowledge and capability is good for the community, for example:

- Central repository for algorithms
- Centralised training
- Best practices data storage transfer and processing
- Forum for community discussions
- Possibilities and best practice for remote access

Attendees identified the following hubs for tomography research (Which is not intended to be an exhaustive list of every micro-CT scanner, which is understood to currently number >100 in the UK):

Area	Hub
North West	Manchester, Huddersfield, Lancaster, Sheffield
South and SW	Southampton, Exeter, Bristol, Portsmouth
Midlands	Nottingham, Warwick, Birmingham, Leicester
London	UCL,IC, NPL, NHM, QMUL, Crick
Wales	Cardiff, Swansea
Cambridge area	TWI, U Cambridge
Scotland	Strathclyde, Dundee, Aberdeen
Oxfordshire	Oxford, Harwell, Diamond, RFI
N. Ireland	QUB (polymers). No large activity
Government related & industry	TWI, AWE, NPL, Catapults, British Museum, MTC, QQ, DSTL

In general an improved catalogue of instrumentation, software, in-situ hardware is required alongside better guidelines for accessing facilities (although some hubs already have clear structures in place). Similarly a skills data base or forum would be beneficial, particularly for new and industrial users.

Standardisation is a major requirement for the X-ray tomography community, and particularly for those engaged with dimensional metrology – this includes a substantial pull from industry. Topics of interest include:

- Reproducibility of scans
- Standard Resolution Measurement
- Standardisation between scans, machines
- Metrology, verification –(ISO10360)
- Reference standards
- Calibration, traceability and uncertainty

This standardisation is not limited to data collection and hardware, but also encompasses data processing and analysis:

- Error analysis
- Image uncertainty

- Feature uncertainty
- Digital Volume Correlation

Training is a major requirement from apprentice to post doctoral level and CPD (which may be accredited). As the adoption of X-ray CT proliferates, there are needs spanning fundamentals to hands on training.

Software: the attendees made specific reference to the difficulties of open source packages vs the expense of more user friendly commercial packages. A common theme is the automation of the image collection/reconstruction/analysis pipeline and the desire for correlation across microscopy modalities.

Data handling and archiving was extensively discussed, reflecting the number of users, and the volume of data collected, particularly for time lapse studies.

- Data sharing, management and storage and cost thereof)
- Reliability
- Metadata capture of scans
- Responsibility/ownership and data legacy

Links to other disciplines: whilst the roadmap sits within EPRSC remit, there is substantial inter-disciplinarily within the UK X-ray CT community and cross research council discussions (EPSRC/STFC/MRC/BBSRC/NERC) were considered valuable, as well as ensuring integration from theory to practice across the experimental and computational research communities.

Impacts: The Town Hall discussions on historic impacts of tomography were wide ranging, and a complete survey is beyond the scope of the roadmap. Impacts were categorised according to 'knowledge', 'society' and 'industry/economy'

Knowledge:

- Life sciences (osteoporosis, crop science),
- Palaeontology,
- Taxonomy
- Energy materials
- Corrosion
- Structural integrity and understanding of repair processes
- Nuclear radiation damage
- Additive manufacturing
- NDT
- Medical implants
- Oil and gas reservoirs

Society:

- Crime and forensics
- Historical Knowledge
- Health/Quality of life
- Climate Science

- Air Quality
- Resources/sustainability
- Security/Safety (e.g. airport security)
- Connectivity
- Energy and resources

Tomography was also identified as a key educational tool, with intangible benefits for STEM education, and public understanding of science

Industry/Economy:

- Energy Industries
- Health and Pharma
- Manufacturing/Product design and QC
- Environmental impacts
- Safety
- Aerospace
- Pharma and healthcare
- Transport Industries
- Quality Control
- Energy
- Food
- Defence
- Consumer goods

In addition X-ray CT itself has had major benefits to UK Plc as a leader in the development of X-ray systems, detectors, sources and software.

Opportunities for future developments which span knowledge, societal and economic impacts were also identified, these included:

- Oil/Gas retrieval
- Batteries and energy materials
- Energy
- Turbine blades and additive manufacturing
- Nuclear fusion
- Metrology and quality control
- Traceability
- Tolerances with standards
- Reliable simulation
- Medical diagnosis
- Inspection of medical devices
- Implants and biomaterials
- Drug production
- Metal casting
- Structural integrity
- Construction

- Smart materials
- Materials development
- Security screening (chemical sensitivity, speed)
- Safety – nuclear, aerospace

Future Needs: New directions for X-ray Tomography were discussed including:

- Colour tomography i.e chemical composition
- Phase contrast modalities
- New materials for x-ray detectors
- High brilliance, tunable x-ray sources
- Advances in CT detectors (having applications outside of CT)
- In-line CT for quality control
- Multi-dimensional information and knowledge
- Range of energies, and low dose tomography
- Very fast scans
- Lab based high speed studies
- Knowledge transfer to community to enable 'self-build' systems
- Balance: lab vs synchrotron is very important

Improvements identified to make further impacts in industry include:

- Multi material
- In-line process control
- New applications would be opened up if phase contrast was in the lab (composites, food stuffs)
- Greatly improved virtual design
- Large volume CT
- Industry needs sources with increased resolution and auto-analysis
- Very high energy CT (MeV to 10MeV) fir huge, dense structures

A workshop session concluded the Town Hall Meetings, with delegates asked to converge on the most pressing future needs in the field:

Future Needs (Manchester)

1. Faster: Sources, detectors, software

2. Correlating modalities: phase contrast, diffraction, colour imaging

3. Infrastructure: Data handling, storage, knowledge transfer, education

Future Needs (London)

Group 1

1. Scanning the un-scannable: portable, hazardous environments, sample size and type
2. Speed and Automation: data collection, analysis and storage, reconstruction
3. Training and Networking (from apprentices to senior management)

Group 2

1. Better Machines: universal, tunable, portable, sample size vs resolution

2. Use machines better: new imaging modalities and scanning protocols, phase contrast, colour imaging
3. Totally integrated software pipeline: automation to 'Solve the Big Data Problem'

Survey of Instruments and Facilities

Respondents to the major user survey were asked to opt in to further contact if they were responsible for the management of user facilities. We identified user centres and interviews were conducted with facilities staff to gauge more detail about operational practices and trends. This section summarises the survey of instruments and feedback from facilities staff:

How X-ray CT is currently employed at facilities?

There is a significantly higher proportion of people scanning samples in the 1 mm to 10 cm (66 %) range.

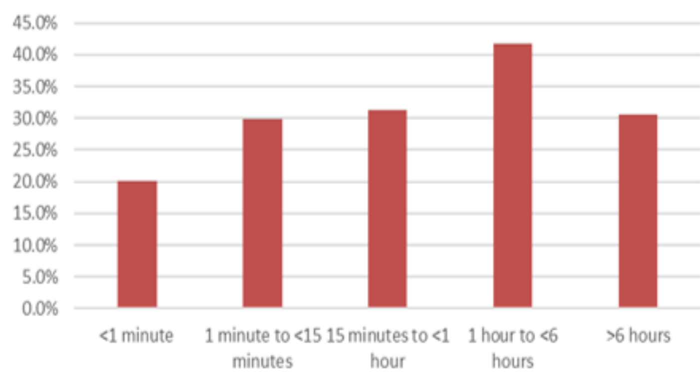
Nearly one quarter of people were scanning items <100 μm in size. To achieve the best resolution of such an item you would require a system with <100 nm pixel size. This could be achieved on the Zeiss Ultra which is owned by two centres (Manchester, UCL) or at beamlines. The centres have offered themselves as user facilities, so if there is appetite for such scans, users should be directed to these facilities.

Less than 10 % of respondents were scanning samples >1m in size – it is unclear if it is lower because of sample types they normally deal with, or if it is due to their capability. Manchester, Southampton and Warwick identified that they have walk-in hutches which are able to handle such sample sizes.

Regarding beam energies used, the most common category was 50 kV -150 kV (70 %). 18 % of respondents use >250 kV: Warwick, Manchester and NCC have 320 kV sources, Southampton, MTC and Warwick have 450 kV sources and Warwick has a 750 kV source. This indicates an industry leaning requirement of high energy given responses from catapult centres.

17 % of users use 1 kV – 10 kV, which would correlate to the use of Zeiss Ultra and beamlines.

75 % of users are scanning with pixel resolution in the 1 μm – 100 μm range (which is notable that 25 % of users don't). This is the range for a "standard" X-ray CT scanner which implies that ¼ of users focus on either very large objects or very small ones – each of the extreme categories (<100 nm, >100 μm) are used by approximately 20 % of users.



Both town hall meetings cited increased scan speed as a future need. The response from facilities here was that the current state of the art does not meet requirements. This issue could potentially be improved with a better knowledge of reconstruction across all centres – the survey showed there is a desire for this knowledge as users generally understand that advanced reconstruction can be used to achieve results with fewer images, but have limited knowledge of how to implement it (this was also heavily discussed at the town hall meeting).

The majority of users are scanning in times longer than 15 minutes, with the highest proportion in the 1 hr – 6 hr band. With this said, 20 % of users have scanned in times less than 1 minute.

Outside of standard lab facilities, over half of X-ray CT users utilise a synchrotron source, and of those, 76 % use Diamond, while 42 % use another European synchrotron and 18 % use a USA based source.

As previously mentioned, just over a fifth of users stated that they are using time-lapse tomography, although 45 % of users are performing in-situ/operando studies. This could correlate to the future need for speed – users performing in situ studies that are too quick to capture with current tomography capabilities. Nearly half of respondents have used a 'rig' in their tomography, of which 60 % are performing tension/compression experiments. The next most common is heating with 44 %, with other responses including cooling, fatigue, indentation, fluid flow, electrochemical, detonation, corrosion, and gas/pressure systems.

It was discussed at the town hall meeting that people wanted access to more rigs but didn't know how, particularly as it seemed wasteful to keep buying the same ones for one-off experiment sets. It was suggested that an online directory be setup in this respect.

According to responses, X-ray CT is currently being used for diverse range of specific applications. Particularly, however, X-ray CT is most commonly being used for dimensional metrology and non-destructive analysis in industrial applications, visualisation in medicine and other biosciences, and in ancient life studies.

Access: A majority of respondents (62.7%) reported not owning their own instrument. Of the responders that own instruments, 70.4% reported that their instruments are available as a user facility, of which 83.7% were happy to be contacted by the working group at a later date about their facility. Over 70% of systems were less than five years old, with approximately half of these being under two years old. EPSRC was cited in part or in full as the most common funder for systems, with many of the remaining funding coming from universities. Of the responders that own an instrument, 50% own more than one.

The Role of Large scale facilities

The large facilities cut across the activities of the UK X-ray-CT community in science, hardware development, software and support infrastructure. Complementary neutron imaging modalities and corresponding infrastructure are only available at large scale facilities (Although these are not considered in the scope of this roadmap).

Large data volumes, data management, cluster and cloud computing are a core activity at large facilities and an area where they should be able to provide the lead. While processing during an experiment is possible on the facility systems, the hosting and processing of that data after the experiment needs a common solution. Support for cloud based solutions with the associated processing tools, driven and developed with the large facilities are underway but should be a priority and resourced to meet a wider community need.

The high throughput at the large facilities has put an emphasis on workflows and the development of robust processing methods and general purpose solutions. Diamond has, for example, been developing a processing framework, SAVU, in which users can then submit tools as plugins which are then available to all and scalable. It's hoped that by developing the workflow that a repository of tools and methods which can be maintained and built on in the long term by the community.

The use of machine learning/AI is seen as a transformative tool in fast imaging and segmentation analysis. Initiatives with the Alan Turing Institute are under development and the mix of computing infrastructure, available training data sets, and theory and analysis benefits from a facility focus. Further challenges exist in the presentation and visualisation of the segmented, quantified data across four or more dimensions with further challenges where the information includes fields (e.g. strain).

Correlative imaging is another area where there is much potential at the large scale facilities: the life science community, through the Rosalind Franklin Institute, have focused on the complete workflow from sample handling across instruments to analysis which may provide guidelines for best practice which can be adopted more widely. The large facilities have tools for multi-scale studies imaging and tomography but driving science cases or community focus is needed to provide this same level of integration.

In the area of training, it's recognized that the large facilities need to play a more active role in particular using webinars and hosting online resources and they can become a hub for such activities. However issues arises around the diverse use of tools used by the community and the facilities realistically need to focus against a core set of, preferably open source, tools which they can provide, deploy and support with users.

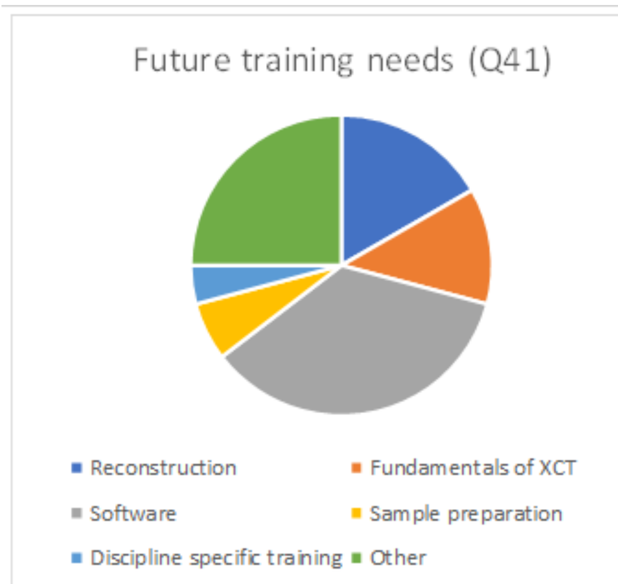
Sample environment development is science driven and the large facilities cannot build in-situ setups to meet the needs of every science area nor can they build the expertise needed in these areas. They must restrict the range of facility supported rigs to a few strategically important areas which have been identified and prioritised by the wider community. They do however deal with the problems of transferring, operating, installing and triggering these science specific rigs and they can more formally provide a lead on standards for signals, connectors, materials, safety interlocks and testing of the rigs. This could help with the wider sharing of these resources across labs and facilities.

The large facilities can be a hub for collaborative technique development and new science. Models that bring the scientists or developers in the community closer to the facilities by embedding them for periods of time with computing or beamline groups would be a positive benefit to both.

Training and Networking

Feedback from surveys and town hall meetings identified a significant need for people development, in parallel to needs in hardware/software. This section will consider the training and networking provision and requirements for the UK X-ray CT community:

The typical work flow in X-ray CT has three constituent parts: scanning, reconstruction and analysis. Under future training needs to best use the technology, five themes were highlighted as shown: fundamentals of X-ray CT, sample preparation, reconstruction, software and discipline specific training (e.g. dimensional measurement).



A user need not have a deep understanding of the methodology and may just want numerical or qualitative results – in fact 63% of those surveyed classified themselves as "users".

There is not one single piece of software that the community uses as they have different specialisms. This inevitably means that different centres/user-bases will have different capabilities and levels of expertise, and could explain the high proportion of "Software" as the response to this question about training.

Continuing with the question regarding future training needs, reconstruction had the second largest amount (17%) with some respondents specifically mentioning that they didn't understand how to use the open source reconstruction packages in this respect. This is clearly a growing area that other researchers want to exploit but indicate they don't understand how (or maybe why they should?).

This is further confirmed by 25% of respondents to the question 36 "what are your future software needs" mentioning some form of reconstruction. Understanding the fundamentals of X-ray CT was closely followed with 12% of respondents mentioning this. Each facet of X-ray CT scanning was mentioned as a training need and was discussed further in the town hall meetings.

Members of the community have garnered their current X-ray CT knowledge through several methods as discussed at the town hall meetings:

- Manufacturer/supplier training
- Courses/pre-conference workshops
- Software training is currently available via Manchester MXIF who regularly hold Avizo courses (at cost), NERC fund courses in ImageJ (held at NHM), and the two main UK conferences ToScA and dXCT hold pre-conference workshops in Avizo and VG Studio.
- Internal "trickle down" training

Participants at the town hall meetings recognised that internal training is the most often used route, but also the most wasteful: we are recurrently teaching the same things across all institutions which use valuable researcher time. 12% of respondents to question 41 “training needs” directly referenced this, citing the requirement for at least an introductory course.

For this very reason, the Manchester Town Hall meeting identified “infrastructure” as a future core need which included more unified training and knowledge transfer. Due to the non-centralised nature of training there is a disparity in ability between centres, but also no clear standardisation in terminology or technique.

London discussed further that if it were to be standardised in such a way, some form of accreditation should exist to confirm that their knowledge meets the expectations of the community. Both meetings independently identified that there is currently no CDT in the technique which could help fill this gap and must cover instrumentation, reconstruction and image analysis techniques. It could then filter down further to different specialisms.

A quote from the town hall meeting in London summarise the room for improvement in this area well:

“Capability is not just hardware – it includes experts, new trainees, students and support roles. We need more researchers to analyse this data. Where are they going to be trained and how?”

Networking: Both the online survey and town hall meetings have revealed the lack of centralised resources/repositories. This specifically relates to:

- What equipment is where, including in-situ rigs available to share
- What software and analysis expertise is available?
- A significant proportion of the respondents, 45.3% actively use in situ/operando tomography, however there is no current mechanism to ‘share’ those resources, potentially leading to a case of ‘re-inventing the wheel’
- Which centres have specialist application knowledge and in what?
- Communication of cost models and user facility access

Within the CT community, networks of CT users exist, however those networks can be fragmented, poorly understood and with limited accessibility. The most commonly identified mechanism to accessing networks is through attending conference and symposia. The following conferences have been identified as the key meetings attended by the participants;

- Tosca (now international)
- dXCT (national – NPL, industry focus)
- iCT (Ghent – European)
- IC3D (Imperial College, national)
- SPIE (America)
- XRM (International)
- XEN network (European, US. Zeiss, manufacturer only)
- Diamond (Advances in X-ray Imaging)

The tomography community is well represented in strategic initiatives, including the Royce Institute, Faraday Institution and RFI where there are active tomography users engaged, as well as the ATI where there is activity in image processing and reconstruction.

Impact Case Study

A good example of an industrial use of CT is Rolls-Royce Plc. Advanced Blade Casting Facility (ABCF) based in Rotherham. The ABCF is a Turbine Blade casting facility that strives to be the most advanced facility of its kind in the world. It has introduced many new technologies, and large amounts of automation to turbine blade manufacture to allow it to meet the growing demand for more complex turbine blades to support engine efficiency and performance improvements.

One of the key enablers to improving the performance of the turbine blades is through better understanding, and control over wall thickness of the blades themselves. Previously this was done using ultrasonic probing in localised areas, but as the blades become more complex to meet customer demand and expectation this technology is reaching the limits of what is capable.

Using CT it has been possible to look at turbine blades in a way that Rolls-Royce has never before explored. CT technology is used both in the wax injection stage using 3DCT to inspect both the ceramic core for defects and dimensionally inspect the wax pattern for conformity. Using CT this early in the process prevents waste, and increases consistency of parts through better understanding of the injection process. Currently the ABCF has 3, 225 kV CT machines, with room for further expansion.

The second use of CT in the ABCF is for final inspection of wall thickness for turbine blades. Due to the dense Nickel super alloys used, and technology limitations at the time of installation only 2D inspection is done at this stage. The use of radiography has been validated for final inspection in the ABCF, and every blade manufacture in the facility is checked for dimensional conformity this way, this allows Rolls-Royce to inspect the blades to a level that has never been previously possible. The validation of the 2D method has also shown a significant improvement in the repeatability of the systems, and the accuracy against a reference in comparison to the previous ultrasonic inspection method. Currently the ABCF has 5, 450kV 2D inspection systems installed on site with room for more systems if required.

The target for the ABCF is to manufacture in excess of 210,000 turbine blades per year, each that will require inspecting using both methods of CT described above. The current facility capacity is 105,000 blades per year, and as of June 2018 the ABCF has been able to demonstrate they can hit this rate, and have on a consistent basis. In terms of week numbers, the ABCF needs to inspect 2000+ blades per week using CT.

It is envisaged that in the future it would be possible to combine many other operations into a single operation using CT, if external, internal, and defect detection could be combined into a single system this could demonstrate huge benefits in cost, time, space, and convenience for the inspection of Turbine Blades.

Steven Bosworth Rolls Royce ABCF

Roadmap Findings & Recommendations

X-ray CT has had profound impact across a range of disciplines and the UK has been world leading both in technique development and applications driven research. Through a range of data collection methods, this roadmap has synthesised the current state of the art for the UK X-ray CT community, and identified future areas for support to retain the UK's leading position in this field.

This roadmap is a 'living' document, which will be periodically updated, the findings from the first phase of this process are summarised here:

Findings

- X-ray CT is proliferating quickly, with users spanning many disciplines, increasingly looking to CT as part of a standard portfolio of techniques (e.g. alongside electron microscopy), in spite of this, the infrastructure for CT is not as developed as other imaging modalities and there is capacity and demand for new instrumentation
- X-ray CT provides unique information, and users are conducting increasingly sophisticated experiments including time lapse and in-situ studies, as well as using advanced imaging techniques (colour imaging, phase contrast): standardising these techniques and improving their availability for the wider user community is important
- We should remove barriers to entry for new users by provision of centralised facilities (hardware, software) AND expertise to advise/assist/mentor new users
- There are no universally adopted standards for tomography (resolution, metrology etc) and these should be developed, building on international programme efforts (eg ASTM)
- There is significant scope for the UK to continue international leadership in the technique development, in particular the translation of tools from synchrotrons to lab facilities: to achieve this we must remain competitive particularly with Germany and the USA
- A range of future needs have been identified by the user community to enable science and engineering research across a breadth of disciplines, these include improvements to temporal and spatial resolution, availability of new imaging modalities (phase, colour, crystallography) and new in-situ/operando methods
- Large scale user facilities (e.g. Diamond) and laboratory X-ray CT suites are highly complementary, whilst many respondents are using both, there is scope for better integration between lab and synchrotron imaging facilities
- Data handling and archiving is an acute and worsening problem as time lapse, multi-scale and fast imaging become increasingly widespread
- An improved understanding of the available instrumentation, software and expertise is required, for example through a central data base
- The cost of access and geographical spread of instrumentation can be limiting for users, for those operating facilities, long term, strategic support is required to maintain and improve provision for the user community
- Hardware and software should be better integrated with the potential to automate the workflow from collection to analysis, and simultaneously improve throughput and data handling

- Capability is not just hardware, and we must as a community continue to develop and train users at all levels: initiatives to support this (training, PhD studentships, fellowships) are welcomed
-

Recommendations:

- There is capacity and demand for new instrumentation, a coordinated capital investment to support this is required, alongside longer term funding to provide strategic access to facilities

- Support is required to consolidate the UK's world leading position in the X-ray tomography landscape, and to retain international competitiveness; this includes mentoring and development of early career researchers, training and outreach as well as co-ordinated financial support across the UKRI portfolio (not limited to EPSRC)

- Training is critical from occasional operators through to experienced researchers and the UK community should consolidate and grow its training portfolio to support the continued use, development and diversification of X-ray tomography

- Suitable standards are essential if X-ray tomography is to be more widely adopted as a metrology tool, the UK should develop new standards and protocols, alongside international efforts

- The UK community should continue to champion new technique development with new X-ray imaging and correlative modalities; this thought leadership will retain the UK's leading edge in the X-ray tomography landscape, and provide a platform for applications driven science and engineering research

- A coordinated approach to cataloguing hardware, software and data is required, for example via a 'kit catalogue' of available equipment, a community library of software and a shared active of open source data

Appendix 1: Expert Readership Feedback

In Autumn 2018, a draft version of the Roadmap was circulated to an international panel of volunteer Expert Readers. Their insight has informed revisions to the current version of the roadmap document, as we view the Roadmap as a 'living document', their suggestions will also inform future iterations of the Roadmap. A paraphrased summary of the Expert Reader's comments are included below:

Gaps

- Although, major challenges are identified relating to image reconstruction, the survey, in particular for the industry, appears to have less focus on software than on hardware.

- The roadmap mostly focused on materials/engineering applications with fewer references to e.g. imaigng of soft biological tissues which is one of the pillars of CT research at the ESRF and other synchrotron facilities, but this probably reflects the nature of the UK community.

- I think in vivo microCT for longitudinal studies in animals should be mentioned as an important topic

Major challenges for X-ray CT Users

- Adequate training - underpinned by the even more significant challenge of motivating young scientists.
- Speed in lab-based system is possibly the biggest challenge as far as in situ, in operando and dynamic studies in general are concerned.
- Sharing of data for benchmarking for correlative imaging
- Bring as much as possible from the synchrotron sources to the home laboratories
- Avoid reinventing the wheel both when it comes to hardware (as rigs) and analysis software
- Need for development more in the areas of multi-modal, in-situ and in-operando use of the technique and in the software development and standardization for analysis
- Access to equipment, robust and time effective quantitative analysis of results, metrology guarantees.
- Time resolution (lab) access to in situ cells/rigs and data processing (workflows, rigour

Major opportunities

- Multimodality and multi-scale approaches.
- Access to phase, dark field, colour imaging and to some extent diffraction can open completely new horizons - both in terms of new science and "real world" applications.
- The major asset compared to e.g. microscopy is of course the non-destructive nature allowing 3D and 4D (x,y,z,time) measurements.
- The technique is still under utilized in research and industry and therefore access needs to be made easier and cheaper so that more people can use it.
- Correlative (integration with other 2D, 3D and 4D methods)
- Time integrated scans
- Iterative reconstructions.
- Still little use because considered as too expensive.
- There is great potential for full transformation of CT into a fully fledged metrology method (something that to some extent has already begun).
- 4D measurements for the better understanding of material failure behaviour and the analyses of changes of biological tissues over time
- Airport baggage scanners show that with enough effort on the software aspects of the reconstruction and data analysis it is possible to make a powerful real time tool. With effort this could be applied to many industrial problems
- New potential impact for CT in resource security/sustainability. Energy: CCS, Nuclear, hydorocarbon, geothermal, energy storage. Materials: water, metals, soil, mining/extraction tech, more efficient use of resources in future materials

Community Requirements

- Setup courses
- Enthusing and motivating students is key here - at all levels.
- Training for software (reconstruction and analyses)
- Consider thematic hubs as well as geographical hubs suggested
- To produce powerful and meaning image analysis, a good understanding of the physics and practical aspects of data acquisition are needed.

UK Capability and Future Needs

- I agree with the roadmap findings - the UK is on the forefront and has a real potential to become and remain world-leading with appropriate investment. For this to happen we also need to invest in new developments and operational capabilities (phase, dark field, colour etc) as this would enable us to remain world-leading in the longer term. Another key element to consider is funding technical personnel in leading labs - often running the machines is handled by postdocs which a) tend to have a significant turnover, and most of all b) should be concentrating on the science - to the benefit of the research group they belong to and especially of their career!
- The community should share more of what is developed.
- This Roadmap is a strong initiative serving both to highlight the current UK capability, capacity and wishes for the future development.
- It is still very expensive and difficult to access X-ray CT equipment in many cases. Also as well as acquisition many users, industrial and academic need a lot of help in processing and analysing their data. If they cannot pay for this time it is difficult to accommodate.
- Report has it about right, we can be world leading in depth and breadth if we are strategic and support more cross and interdisciplinary wok and continue to grow access and skills base

Additional Comments and Suggestions

- The possible direct networking between users (including university experts) and the companies selling and developing X-ray CT. Such a network could indeed help in developing user-friendly reconstruction software to the benefit of both the users (from both industry and academia) and the X-Ray CT companies

- X-ray CT is supported across the EPSRC remit, but is of equal potential across other physcial and bioscience elements of UKRI, areas where world leading research with high economic and societal benefits (GCRF and ISCF) is also being done. EPSRC equipment and STFC facilities underpin this research. Other RCUK streams are less supportive of lab CT acqusition costs.

- Possibility of having some centralised repository of data collected in different projects and that could be re-used by others (as example for benchmarking)

- This is also in line with the EPSRC guidelines for project holders to share data used for paper published and acknowledging EPSRC funding.

- The roadmap is excellent. Although it is not perfect, the reader finds the coverage to be extremely thorough. The information appears remarkably complete

- The roadmap points out current state of the art and demands. It does talk about future needs as well. The reader agrees with roadmaps conclusions and complete nature of coverage.

- Learning from the medical CT community may be advantageous.

- The reader appreciates the brief and summary nature of the roadmap, but there are some omissions or incomplete topics that the reader thinks are important enough to mention:

  - ASTM has standard for CT; the discussions of many topics such as resolution standards are quite good. Further, as the UK standardization effort goes forward, the reader, who has no affiliation with the ASTM effort, encourages building on what was done earlier by ASTM.

  - There is a topic that is extremely important and which the reader missed in the document: local tomography (a.k.a. region of interest tomography). The reader is unaware of such scanning outside of synchrotron radiation sources, but there may be capabilities on one or more commercial systems.

  - There should be a listing of the tomographic packages out there at present.

  - The roadmap talks about complementary techniques: X-ray scattering (diffraction) tomography should be mentioned as well as fluorescence tomography, ptychography and laminography approaches

Appendix 2: Steering Committee

Prof Paul Shearing, UCL - Chair of the steering committee
Dr Martin Turner, University of Manchester
Prof Ian Sinclair, University of Southampton
Prof Peter Lee, UCL
Dr Farah Ahmed, Natural History Museum and Exponent
Dr Paul Quinn, Diamond Lightsource
Prof Richard Leach, University of Nottingham
Dr Wenjuan Sun, National Physical Laboratory
Dr Jay Warnett, University of Warwick
Prof Hugh McCann, University of Edinburgh
Prof Andrew Harrison, Diamond Lightsource
Dr Claire Higlett, EPSRC

Appendix 3: User Survey

Contact details
Name
Institution
Email

Background:

1. What discipline are you from?

- Engineering
- Materieals Science
- Biosciences
- Medical
- Life Sciences
- Ancient Life
- Other

2. Techniques: What techniques do you use?

Please select all that apply

- Ø Multimodal: Correlative imaging (SEM, XCT, TEM)
- Ø Multimodal: Multiscale X-ray CT
- Ø Multimodal: other
- Ø Image based Modelling
- Ø Time-lapse: Tension/Compression
- Ø Time-lapse: Fatigue
- Ø Time-lapse: Fluid Flow
- Ø Time-lapse: Corrosion
- Ø Time-lapse: Heating
- Ø Time-lapse: other
- Ø Colour X-ray Imaging
- Ø Synchrotron Imaging
- Ø Phase Contrast Imaging
- Ø Other

3. What do you use X-ray CT for?

- FREE TEXT

4. Do you own an instrument? (if so what)

- Yes/No check box
- Free text answer

5. Do you offer this as a user facility?

- Yes/No check box
- If yes, box to follow up ‘Can we contact you for further information?’

Hardware

6. What sample sizes do you most commonly scan?
Please select all that apply

- <100 micron
- 100 micron to <1mm
- 1mm to < 1cm
- 1cm to < 10cm
- 10cm to <1m
- >1m

7. What beam energies do you utilise? Please select all that apply

- <1kV
- 1kv to <10kv
- 10kV to <50kV
- 50kv to <150kV
- 150 to <250kV
- >250kV

9. What is the best pixel resolution you require?
Please select all that apply

- <100nm
- 100nm to <1micron
- 1 micron to < 10 micron
- 10 micron to <100 micron
- >100 micron

10. What is the best time resolution you require?
Full 3D image in:
- Ø <1 minute
- Ø 1 minute to <15 minutes
- Ø 15 minutes to <1 hour
- Ø 1 hour to <6 hours
- Ø 6hours

11. Do you use synchrotron sources (if so, which)?
Please select all that apply

- Ø Diamond
- Ø ESRF (France)
- Ø Soleil (France)
- Ø BESSY (Germany)
- Ø SLS (Switzerland)

- Ø Elettra (Italy)
- Ø APS (Argonne, USA)
- Ø SSRL (Stanford. USA)
- Ø NSLS (Brookhaven, USA)
- Ø Other – Free text

12. Do you use in-situ/operando tomography?

Yes/No check box

If yes:

Please select all that apply

- Heating
- Cooling
- Tension/compression
- Fatigue
- Indentation
- Fluid flow
- Electrochemical
- Other (free text)

Algorithms and Software

13. Which reconstruction software do you use?

- Free text answer

14. Do you develop reconstruction algorithms in house?

- Yes/No

15. Which image analysis software do you use?

Please select all that apply:

- ScanIP
- Abaqus
- Avizo/Amira
- MATLAB
- VG Studio
- ORS Dragonfly
- Star CCM
- COMSOL
- DVC
- Other (free text)

16. Do you develop code for image analysis in house?

- Yes/No

17. Please identify any software development needs

- Free text

Challenges

18. What is the current major challenge facing your work in tomography?
Free text

19. What technical developments would improve your results and enable new science using tomography?

- Free text

20. What teaching activities, training or workshops would you find beneficial to your research?

- Free text

21. Any other Comments?

- Free text

Appendix 4: Industry Survey

Contact details

Name
Institution
Email

Background:

1. What industry are you from (Check all that apply)

- General Engineering
- Aerospace
- Other transport sector
- Materials Science
- Biosciences
- Pharma
- Other life sciences
- Medical
- Earth Sciences
- Energy
- Food and consumer products
- Manufacturing
- NDT
- Other

2. Do you own an instrument? (if so what)

· Yes/No check box
· Free text answer

3. Do you use a commercial or University service provider? (if so, where)
Yes/No check box
Free text answer

If yes, what is the typical wait time
<1 week
1 week to 1 month
1 month to 3 month
3 months to 6 months
> 6 moths

4. What sample sizes do you most commonly scan?
Please select all that apply

<100 micron
100 micron to <1mm
1mm to < 1cm
1cm to < 10cm
10cm to <1m
>1m

5. What feature sizes do you need to resolve?
Please select all that apply

<100nm
100nm to <1micron
1 micron to < 10 micron
10 micron to <100 micron
>100 micron

6. Do you use in-situ/operando tomography? (Where you replicate an environment such as temperature or applied stress whilst scanning.)
Yes/No check box

If yes:
Please select all that apply

- Heating
- Cooling

- Tension/compression
- Fatigue
- Indentation
- Fluid flow
- Electrochemical
- Other (free text)

7. What is the current major challenge facing your work in tomography?

· Training
· Availability
· Sample size limits
· Resolution limits
· Scan speed/throughput
· Data processing/feature detection
· Calibration/metrology
· In situ/in operando use
· Cost
· Scanner availability

8. What technical developments would improve your results and enable new science using tomography?

· Resolution
· Accuracy
· Error reduction (quality of scan)
· Larger measurement volume
· Faster scan speed
· Flexibility of scan
· Automation (robotic arm)
· Software improvement