Industry 4.0 Workshop

Report from the Workshop on Structural Integrity, NDT and CM Requirements for Industry 4.0

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BINDT
THE BRITISH INSTITUTE OF NON-DESTRUCTIVE TESTING

in collaboration with:

RCNDE FESI The Alan Turing Institute The Welding Institute

...engineering safety, integrity & reliability

Workshop on Structural Integrity, NDT and CM Requirements for Industry 4.0

The digitalisation of inspection and monitoring to ensure the structural integrity (SI) of manufactured products and assets throughout their lifecycles has been given the term 'NDE 4.0' and has a significant international community dedicated to its development. Despite this, stakeholders in this area have been uncertain as to how to capitalise on the opportunity or where to focus new developments in order to facilitate its exploitation. Many in this community hold the view that the main element missing is the will, amongst potential beneficiaries, to make this happen. In a bid to unpick this conundrum, a group of UK stakeholders organised this two-day workshop to capture some consensus requirements. This report describes the workshop rationale and contributions and summarises the consensus requirement set for the benefit of companies and organisations working in NDE 4.0.

Key requirements identified include:

- *Helping to address motivation by developing business case tools*
- *Supporting regulators and insurers to understand the impact of emerging technology and facilitate incentives to change, as well as influencing the development of legal case law*
- *Addressing the regulatory distortions caused by differing legal treatment of human and machine decision-making*
- *Developing an industry skills strategy to account for approaching demographic change along with emerging skills needed in an NDE 4.0 world*
- *Support for the integration of inspection and monitoring with systems controlling manufacturing, fleet and plant operation and maintenance, and enterprise systems*
- *Approaches that address conformity assessment holistically and integrate with the manufacturing process throughout*
- *Removing personnel from harm's way through harsh environment automation, autonomy and remote inspection*
- *Exploiting digital twins for sentencing and prognostics*
- *Building a unified data ecosystem that many players can contribute to, and benefit from, with contribution and value addition being properly attributed and directed*
- *Evolving 'design for monitoring and inspection' methodology to ensure the optimum mix of lifecycle management interventions for entry into service*
- *Developing standards and open technology to stimulate innovation and reduce risk*
- *Developing clearer functional descriptors of integrity requirements and traceability in the monitoring and inspection metadata set*
- *Assuring the integrity of actionable information in systems employing artificial intelligence (AI), autonomy and adaptation.*

Contents

Introduction

The British Institute of Non-Destructive Testing (BINDT), in collaboration with the UK Research Centre in Non-Destructive Evaluation (RCNDE), the UK Forum for Engineering Structural Integrity (FESI), the Alan Turing Institute and The Welding Institute, scheduled a workshop considering the path to Industry 4.0.

This report captures the outcome and provides a basis for further collaboration around the shared industry goals identified.

Following a short introduction, the report provides summaries of the invited talks grouped by the workshop session themes, a report from the workshop breakout discussion groups and a consolidated summary of the objectives identified during the workshop. Participants have had the opportunity to provide additional comments on the requirements through post-workshop survey responses and to comment on this report prior to publication. Consequently, the organisers believe that this represents an independent snapshot of the community's view of inspection and monitoring requirements to align with Industry 4.0.

Industry 4.0 will completely change the production and operation of nearly every manufactured item in the developed world. Intelligent systems will enhance and sometimes supersede human decision-making in production and operation, and industry will no longer be limited by human cognitive ability. Outcomes will include higher levels of productivity, lower through-life costs and greater safety and reliability, which will benefit industry, the global economy and everyone who uses machines or travels in vehicles.

The autonomous, intelligent systems of Industry 4.0 will need high-rate, complex information about operational loads and structural condition, available non-destructively and throughout life, thereby building confidence in their integrity and reducing costs. Assets could become continuously self-verifying, requiring no external intervention to maintain fitness for purpose. There is a need to bridge the emerging gap between current reality and these visions of the future: the current state-of-the-art falls significantly short.

What are the specific non-destructive testing (NDT), structural health monitoring (SHM) and condition monitoring (CM) requirements that should be focused on to allow for this step change and how will they relate to structural integrity (SI) and design philosophies? This was the focus of the workshop, where experts in these fields met with designers, manufacturers and regulators to determine what success will look like, what challenges will be faced and what steps must be taken.

Understanding Industry 4.0: high-level objectives/aspirations, drivers, business, risk, dynamics and tensions

Theme Chair: Pete Loftus, RCNDE

The first session continued the introductory theme by highlighting a range of views on the NDE 4.0 concept.

Introduction to the delegates

Pete Loftus introduced the workshop in the context of the series of requirements capture workshops facilitated by RCNDE, the details and reports of which are available through the BINDT website.

Introduction to Industry 4.0 and NDE 4.0

The first talk of the day was given by Nick Brierley, Chair of the BINDT NDE 4.0 Group, supported by Robert Smith of RCNDE and Simon Mills of SpectrumCBM. The talk set the scene for the two days by explaining the context for the workshop and ensuring that participants had a similar basic understanding of key terminology and concepts (see Figure 1).

After explaining the basics of Industry 4.0 and introducing the interrelated fields of NDT, CM and SHM, the term 'NDE 4.0' was explained. Drawing on RCNDE documents, the conventional inspection workflow was compared to the potential future inspection workflow. This would encompass the use of the asset's digital twin (DT) fed with continuous non-destructive evaluation (NDE) data and automated processing of sensor data to extract information, in order to achieve a state-specific performance prediction and automated non-destructive verification, as shown in Figure 2.

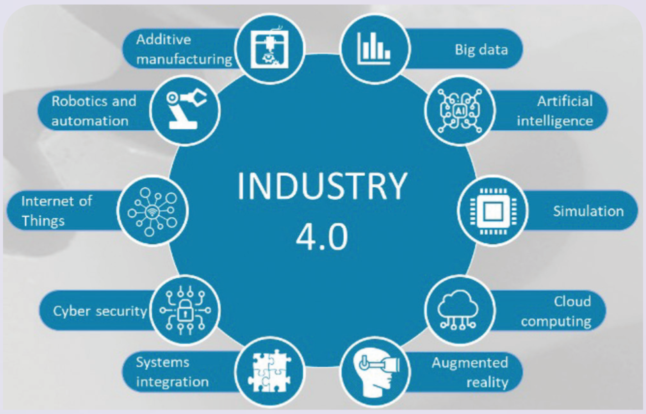

Figure 1. Industry 4.0 technologies

For the purposes of this report, NDE 4.0 can be thought of as the digitalisation of NDT, SHM and CM and integration with wider Industry 4.0 opportunities or the integration of inspection and monitoring into Industry 4.0.

The high-level objectives for NDE 4.0 from the BINDT NDE 4.0 Group's roadmap[1] were explained:

- Improved through-life asset performance
- More efficient production, including of new products
- Better/fast/cheaper NDE – reduced costs of asset ownership
- Efficient quality control (QC) for customised products
- Reduced need for personnel to be in harm's way/travelling
- Efficient QC for decentralised production.

These can be thought of as initial high-level requirements, to be expanded and improved upon over the course of the workshop. It was explained that these high-level objectives were used by the NDE 4.0 Group to derive the required developments and from that a roadmap.

The speaker emphasised the extent to which the transition to NDE 4.0 is expected to not only force the NDT, CM and SHM communities to work more closely together, but also to drive greater collaboration with other communities, such as metrology and materials. These changes, he argued, will be driven by the fact that the domains will increasingly recognise the ability to help each other and the fact that external stakeholders, especially industrial end-users, will expect the different fields to present a single cohesive picture of the fitness for purpose of an asset.

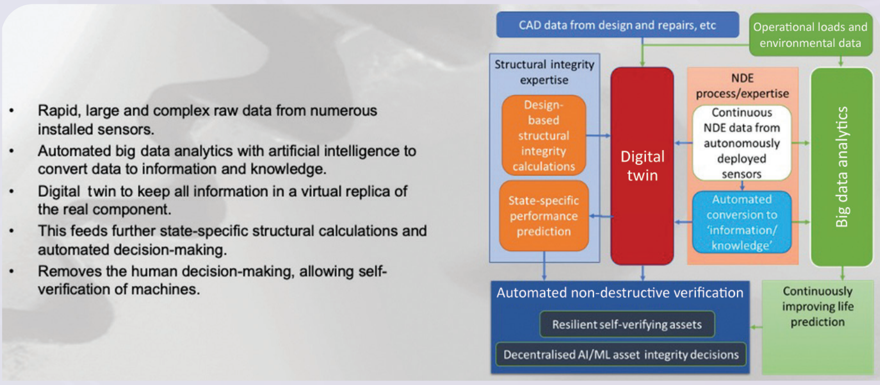

Figure 2. Potential future NDE inspection workflow

Overview of essential topics for the workshop

Paul Wilcox, representing RCNDE, gave an overview of the topics that the workshop organising committee had identified as key and which had informed the structure of the workshop:

1. Understanding Industry 4.0
2. NDE/CM/SHM for structural integrity through the Industry 4.0 lifecycle
3. Skills
4. NDE/SHM/CM benefits beyond structural integrity
5. Collaboration between communities
6. NDE experiences from the field – NDE 4.0 in the present
7. Current research/work for potential future improvements.

He emphasised that elements of NDE 4.0 are already contributing to improved industrial performance while other elements are hot research topics. He highlighted RCNDE's key role as the leading research collaboration in NDE and provided examples of projects the group has supported, and is supporting, in both acquisition and analysis to help deliver NDE 4.0 capabilities.

He also introduced the break-out and panel sessions, which formed the basis of the requirements capture from the delegates.

'Bigger picture' view of the benefits of Industry 4.0 in broader asset management

Martin Wall, HOIS Digitalisation Forum, ESR Technology

Martin Wall presented, on behalf of the HOIS Digitalisation Forum (HDF) and ESR Technology, an overview 'bigger picture' on the key elements and benefits of the use of Industry 4.0 and NDE 4.0 for in-service inspection and broader asset management, with examples of currently available technology solutions and applications.

Conventional practice in asset management is scheduled or risk-based inspection (RBI) that is carried out as part of planned downtime. This is often to written schemes of examination (WSEs); the practice depends on the industry and regulations within the specific country. Inspections are generally spot measurements, sampling or low-coverage methods. Typically, ~85% of inspections are visual (for example for external corrosion) and NDE is often limited to manual ultrasonic testing (UT) wall thickness measurements.

This practice can be costly and time-intensive. Inspection results are added to the plant database or, in older assets, reports are archived and may not be looked at. Integrity and corrosion engineers who have overall responsibility for asset management are often distant from inspectors. NDE is considered as a necessary, if sometimes begrudged, activity. Results are assessed and a new interval is set. Analysis is usually limited to simple trending, unless cracks are found, in which case more detailed assessments are undertaken.

Industry 4.0 and NDE 4.0 offer the opportunity to transform such work processes, to do things better, or do things faster, manage assets more effectively and provide a transformation in the data available and the use and analysis of data. Asset integrity could then be managed on the basis of actual condition data (condition-based inspection) rather than perceived risk.

Industry 4.0 (and NDE 4.0) move from digital automation and robotics to interconnected 'cyber-physical' systems. Key to this is a transformation in work processes: in the data acquired; in the end-to-end data flow from assessment and planning to data collection, to data analysis, to application by the end-user, to taking decisions and updating of the asset integrity management plan; with efficient interfaces, data format and clarity on ownership.

Key technologies are: automated, robotic or large-data systems; the use of more sophisticated data analysis; the inclusion of NDE data in digital twins (through NDE 4.0); and the availability of the full breadth of data, analysis and visual models to integrity engineers to help make decisions on asset management and predicted life. Artificial intelligence (AI) and machine learning (ML) increasingly allow for the assessment of datasets that may be too big or difficult for a human operator to interpret (as in more complex NDE methods such as full matrix capture (FMC) with the total focusing method (TFM)).

How this 'bigger picture' could work is shown in the Figures on page 5. Advanced NDE technology such as robot crawlers or drones, or global methods such as photogrammetry, allow for higher coverage inspection and the acquisition of more detailed and extensive condition data. This is fed into and stored in a 'data lake' or cloud, where it can be made accessible with other digitalised integrity and operational data, for analysis, for life prediction, for input to plant models or digital twins and for evaluation by integrity or corrosion engineers. The data could be used in integrity management, plant operation or for inspection analytics. Rather than assessment from a distance, integrity engineers and inspectors could sit together and assess the data, providing more informed and cost-effective decision-making.

Industry 4.0 and NDE 4.0 technologies can assist at each stage. Simply more condition information becomes available, is better presented and is accessible, with operational and other data in a common visual framework such as a mini or plant-level DT to help integrity engineers reach decisions.

While this bigger picture may be some way off, commercial Industry 4.0 and NDE 4.0 offerings are already in place that provide current digital solutions for NDE data acquisition, data storage and digitalised visual presentation and data comparison for integrity engineers. The application of Industry 4.0, NDE 4.0 and digital transformation is likely to occur where the cost benefit is highest, and most likely in new assets rather than ageing assets where integrity management practices are harder to change.

The HDF (www.hois.co.uk) has become a key cross-industry forum for raising awareness of current technology and applications for digitalisation (including Industry 4.0). Globally, the International Committee for Non-Destructive Testing (ICNDT), the European Federation for Non-Destructive Testing (EFNDT) and BINDT are actively developing forward roadmaps and guidance to address the key requirements and gaps.

Table 1. Key Industry 4.0 and NDE 4.0 technologies and requirements

Key technologies
• Robotics, autonomous underwater vehicles (AUVs) and crawlers
• Digital twins
• Cloud data storage
• Data visualisation
• Automated defect recognition (ADR) and AI/ML
• Laser scanning and photogrammetry
• DTs and mini-DTs (system level)
• Data analytics
Requirements
• End-to-end data flow
• Data storage
• Data format
• Data ownership and access
• Links to plant databases (for example MAXIMO, SAP)
• Integration with plant digitalisation models and DTs

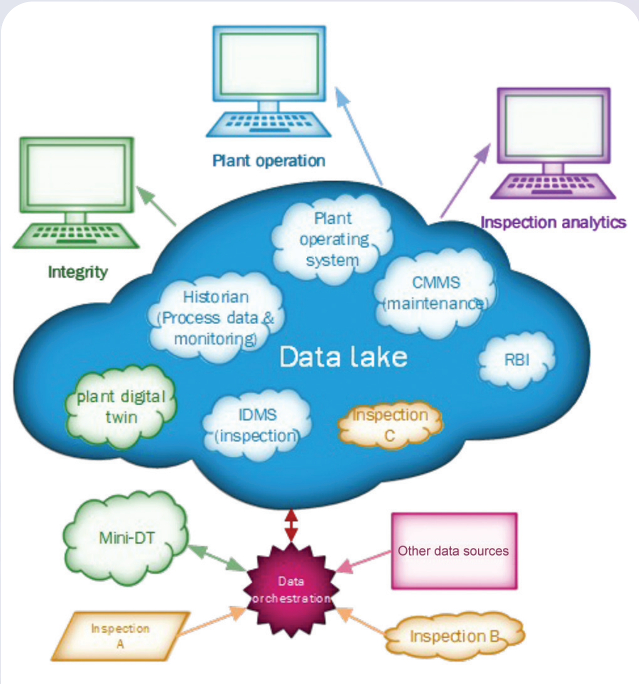

Figure 3. The 'bigger picture' for Industry 4.0 and NDE 4.0 in asset management: 'end-to-end' data flow, stored in the cloud for use in data analytics, plant operation or integrity planning

Assessment and planning	Data collection	Data analysis	Update and actions
• Modelling • Simulation • Statistical analysis • Visualisation • Quantified inspection performance • Data mining • Machine learning	• Inspection data acquisition systems • Transducers • Techniques • Volume of quantified data • Deployment (robotics) • Automation and remote control	• Advanced digital signal processing (large volume) • Machine learning • Statistical analysis • Inspection data QA • Quantified risk • Automation • Delivering insights	• Data- and insight-driven decision-making processes • Ready access to info via AI-driven databases • Statistical 'what if' scenario assessment • Cost-benefit analysis

Figure 4. Software-driven integrated workflow processes using data to support decisions: end-to-end information flow

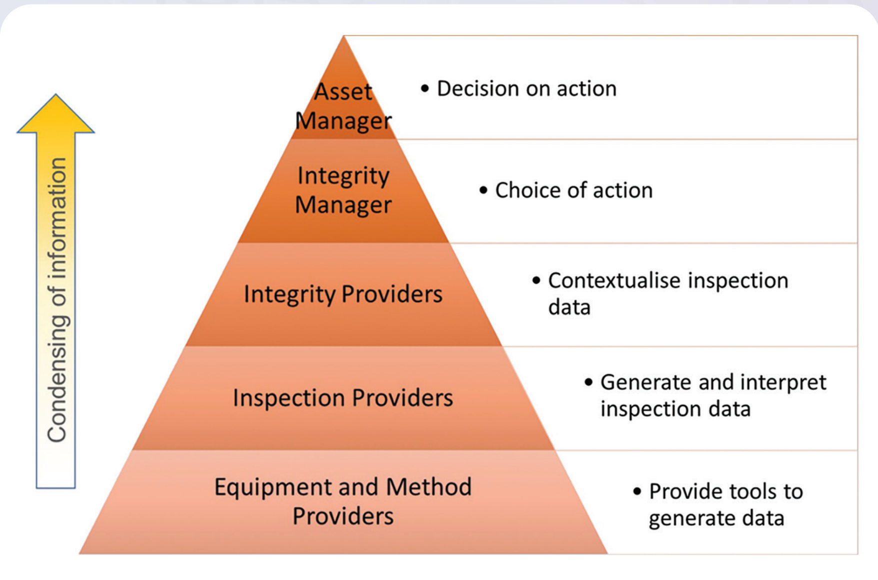

Figure 5. The applications of Industry 4.0 and NDE 4.0 in asset management, from planning, collection and analysis to decisions and close-out

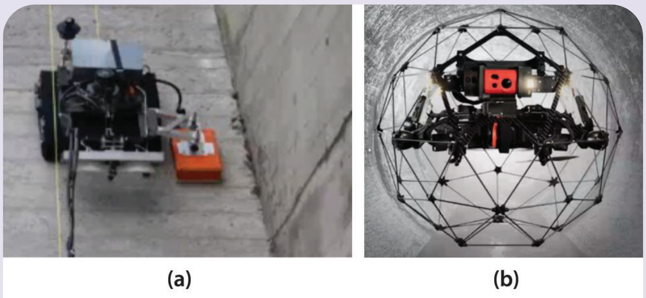

Figure 6. NDE deployment: (a) crawler; and (b) drone

Structural integrity: how will this change and what will NDE/CM/SHM have to provide?

Jim Skelton, Jacobs

This talk focused on the requirements driven by structural integrity management in the nuclear industry. After a brief introduction to the past, present and future of the nuclear sector, Jim highlighted some of the things the technology needs to do:

- Minimise the downtime caused by shutdowns due to inspection
- Utilise models that provide a more accurate (and less conservative) assessment of the plant's state and may incorporate data collected in real time
- Provide robotic inspection systems that can carry out detailed inspections while the plant is operating (*ie* hot and radiating)
- Enable rapid understanding and prediction of emergent issues
- Provide flexible monitoring systems that can have their scope rapidly adjusted to cope with emergent issues.

Jim went on to outline some of the requirements to deliver the above:

Interoperability of systems, software and people:

- Data held in self-describing formats controlled by open standards (for example JSON, AVRO, HDF5)
- Transducers also need to be self-describing (IEEE 1451/TEDS)
- More modular NDE software, for example much simpler integration between the robot moving the probe and the software analysing the image from the ultrasonic phased array.

Combine models and plant data:

- Fit the plant with transducers that measure the key structural elements
- Feed these parameters (and original plant data such as material data) into a structural model that can be used to assess fatigue life
- At the very least, better plant information can start to predict when and where fatigue cracking is likely to be a problem and schedule periodic inspection more precisely.

"A digital twin can be developed when there is a key interactive connection between a physical system and the corresponding virtual model. When measured data from the physical system is provided to a virtual model, a digital twin is formed, and this enables the digital twin output to be much more tuned to the physical systems' performance and can be used to adjust operations or inform future decisions."[2]

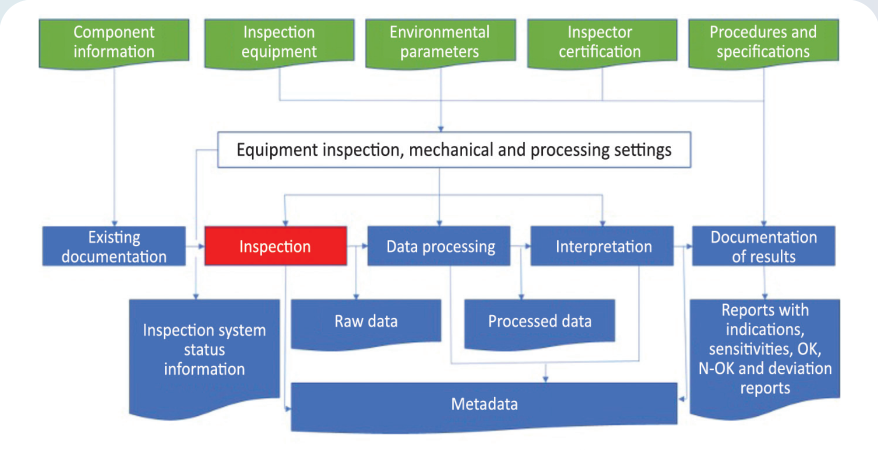

Figure 7. Typical sequence of an automated inspection in serial production[3]

The challenge is keeping the model (and sensing) up to date with emerging degradation mechanisms.

- Acquire more data, better data and data with improved metadata
- Sentencing using models (digital twins) to reject artefacts
- Machine learning and AI adapted to very small training datasets and high-criticality decisions
- Automation facilitated by temperature- and radiation-tolerant sensors and robotic access.

Challenges for robots:

- Autonomous
- Must work in hot radioactive environments
- How are they powered?
- If it is an ultrasonic inspection, how is the ultrasound coupled?
- Is it necessary to change how plant is designed so that it can be inspected by a robot?

Jim concluded by saying that the structural integrity and non-destructive evaluation communities are at a turning point in technology and some of the challenges that we need to overcome are optimisation and mindset.

Drivers for designers and asset owners with Industry 4.0: SI, lifing, past and current philosophy and potential future philosophy

David Wright, Rolls-Royce plc

David paraphrased his talk as 'Industry 4.0: the digital world and NDE'.

He emphasised the need for non-destructive evaluation to integrate with manufacturing systems, reminding us that NDE can be modelled and is capable not only of defect detection but also of informing understanding of the material state and the processing that gave rise to it.

He outlined a typical sequence of an automated inspection in serial production, as shown in Figure 7.

This was developed to show that the opportunity exists to develop the field of non-destructive materials characterisation to provide a lifecycle view of material characteristics and the processes that have influenced them, which, in turn, will support lifecycle optimisation.

Standards for interoperability will be required for raw data, processed data and metadata.

NDE/CM/SHM for SI through the Industry 4.0 lifecycle

Theme Chair: John Sharples, Jacobs and FESI

Probabilistic structural integrity and data-centric engineering

Mike Martin, Engineering Associate Fellow – Structural Integrity, Rolls-Royce plc

This talk introduced the data-centric engineering (DCE) approach shown in Figure 8 in the context of nuclear structural integrity, highlighting the importance of non-destructive examination to DCE and noting the valuable opportunity to recognise NDE more generally as a valuable source of data in contrast to more traditional go/no-go applications.

DCE provides a consistent and holistic way to use all sources of data relating to a product obtained throughout its lifecycle, from raw material and manufacturing through to operation,

Figure 8. Data-centric engineering

maintenance and decommissioning. The data are used to update a digital twin of an individual instance of the physical product that models the structural integrity behaviour through life. Material degradation models, including initiation, propagation and failure, are included in the digital twin as needed. The output from the digital twin is proximity to structural failure, quantified using probability and structural reliability methods. This leads to improved risk-based asset management and infrastructure decisions when compared to traditional deterministic methods that are based on reserve or usage factors and often inconsistent levels of conservatism. DCE enables the worth, or value, of each individual lifecycle data source to be quantified, ultimately providing an approach to focus limited resources to where they are most effective throughout the lifecycle, for example improving inspection strategy, optimising the operational envelope and understanding the relative value of manufacturing process control *versus* in-service monitoring.

As shown in Figure 8, lifecycle inputs to the digital twin can include material properties, as-manufactured geometry, as-operated load/temperature history data together with data from NDE, in-service inspection (ISI), equipment health monitoring (EHM) and SHM. Typically, the digital twin is a finite element model, or a more computationally efficient reduced-order, or surrogate, representation. This is particularly important within a probabilistic framework where many individual trials with randomly sampled inputs may be required, or where smaller length scale approaches such as crystal plasticity methods have been used to account for the influence of microstructure.

The talk described some of the recent advances in probabilistic methods as applied to nuclear structural integrity, citing the EDF-led EASICS (Establishing Advanced Modular Reactor Structural Integrity Codes and Standards for UK Generic Design Assessment) project and probabilistic total-life fatigue approach considered by the UK Technical Advisory Group on the Structural Integrity of High Integrity Plant (TAGSI) NT30 subgroup as examples. Finally, the use of advanced NDE techniques such as the ultrasonic wave speed (UWS) approach to derive crystallographic texture and the application of Bayesian inference techniques to ISI data to update inspection strategy were highlighted as examples of DCE that are currently under development.

An opportunity exists to develop future NDE techniques, together with ISI, SHM and EHM as data sources that can be used holistically within a DCE approach.

Regulatory and liability viewpoint on artificial intelligence/machine learning automated decision-making within the NDE/CM/SHM part of the SI process

Richard Hyde, Professor of Law, Regulation and Governance, University of Nottingham

When new technologies are introduced, the law can be both a barrier to adoption and an enabler. In the discussion of novel non-destructive testing technologies, the role of law and regulation cannot be ignored. This short piece will outline how law and regulation may inhibit adoption and may also act as an enabler.

Regulation

A number of regulatory provisions may require non-destructive testing. For example, the Health and Safety at Work etc Act 1974 requires that employers "ensure, so far as is reasonably practicable, the health, safety and welfare" of their employees (section 2) and other persons who may be affected by their undertaking. To comply, it is necessary to demonstrate that reasonably practicable steps have been taken to ensure health, safety and welfare. Demonstrating that NDT has been undertaken may be a part of that process.

To show that reasonably practicable steps have been taken, it must be shown that appropriate data has been collected, the data has been analysed using appropriate techniques and the results have been acted upon and appropriate steps taken. To ensure that novel NDT technologies are seen as reasonably practicable techniques, it must be evidenced that these steps have been taken. If this is the case, regulators are more likely to accept such technologies as an important part of the business's toolkit and, with acceptance, may move towards requiring such techniques, as they are able to demonstrate increased efficacy compared to traditional techniques.

Legal barriers

Claims may arise when materials that have been tested fail and this leads to injury. In this space, claims are increasingly complex, with an increasing number of actors who may be liable. While the person performing the testing will usually be the person seen as primarily liable, the entire ecosystem (including those who provide hardware and software, those who provide training data and so on) may bear some liability in the event of an injury.

Where novel NDT techniques are used, the user will owe a duty of care to all those who may foreseeably be harmed if the user acts negligently. The negligence may arise either in the use of the technology or in the interpretation of the data. In order to avoid liability, the user must show that they acted to the standard of a reasonable expert in the area. With any novel technology, determining what an expert would do is challenging, as there is a less developed body of professional opinion for comparison.

Beyond the user, the manufacturers of the technology may also be liable if they have acted negligently, for example in the selection of training data or in the ways that algorithms develop. However, liability for negligence in this field is developing and there is not yet the case law available to understand what is expected of, for example, a training dataset, in order for its provision not to be seen as negligent. This may mean that users are unwilling to adopt new technologies for fear of liability (or inability to obtain insurance).

How can the law support adoption of these technologies?

The law can function to support the adoption of technologies by holding that use of the technologies is part of the standard of care in negligence. An example of this is the shift in the standard of care as new medical technologies evolve. Similarly, the regulators, if convinced of the utility of new technologies, may alter regulation to explicitly require such technologies or interpret existing standards to require such technologies.

Open *versus* private data

Richard Rheume, Ondia NDE

Benefits of open data:

- Pooling of data enables new solutions from third parties
- A solution for a lack of training data available for AI.

Benefits of private data:

- A competitive advantage for the data owner
- Easier to protect the data.

Richard challenged the audience to consider what parts of their datasets are critical for the intended purpose, what parts constitute sensitive information, how revealing the data may be (*ie* if taken out of context, what can be learned from the data), whether this can be anonymised in a pool to facilitate collective learning and what parts can be safely deleted. He outlined some of the tools available to ensure that data are only shared for the intended purpose once these constraints are understood.

He cited no requirements for new technology, just the need for data users to understand the opportunities and threats involved in sharing their data.

Figure 10. Definition of new roles[4]

Skills

Theme Chair: Simon Mills, BINDT

Skills, training and qualification implications of NDE 4.0

Nick Brierley, Diondo GmbH and Chair of BINDT NDE 4.0 Group, and Caroline Bull, Director Elect, RCNDE

The discipline of NDE, in common with other related disciplines, is in the process of exploring how it will operate as part of an Industry 4.0 interconnected landscape. This talk highlighted that the move to NDE 4.0 has skills implications that need to be considered, that there are multiple stakeholders to consider and include in planning for NDE 4.0 (see Figure 9) and that there are multiple, presently disjointed, initiatives already underway on NDE skills.

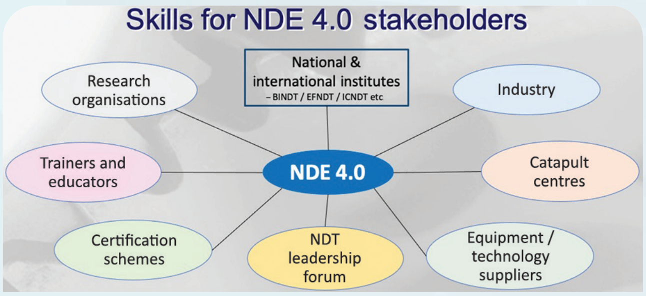

Figure 9. NDE 4.0 stakeholders

A broader way to express the requirements was introduced:

- Human – NDE 4.0
- Human factors
- Personalisation
- Interfaces
- Technology developments and impacts – skills gaps
- Culture
- New ways of working
- New ways of communicating
- Agility/flexibility/adaptability
- Ensuring we are NDE 4.0 skills 'future-ready'.

There are at least two interpretations of likely future NDE roles, as shown in Figures 10 and 11.

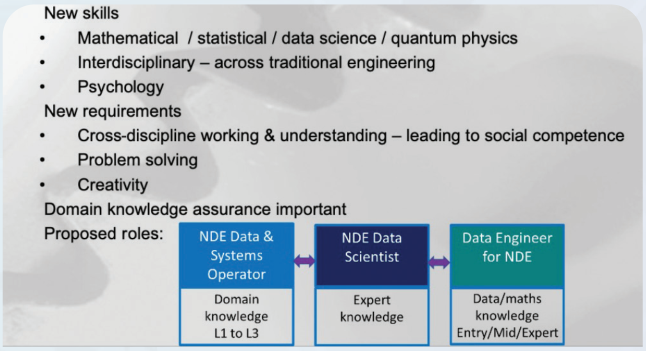

Figure 11. Proposed roles[5]

The BINDT NDE 4.0 Skills Working Group will focus on working with other similar groups to deliver suitably skilled personnel to develop, maintain and use NDE 4.0 technologies through:

- A certification scheme with qualifications such as Levels 1-3
- Recognition of existing qualifications – gap analysis to NDE 4.0
- The ability to respond to the skills gap as technology develops
- The ability to respond in the face of new demands
- The ability to assess and demonstrate relevant skills and competence.

Metrology skills framework – national metrology alliance

Pete Loftus, RCNDE, Trevor Toman, Coventry University, and Phil Bamforth, Rolls-Royce plc

This talk introduced an initiative from one of NDE's cognate disciplines, with synergies that the NDE community can both support and learn from. The National Metrology Skills Alliance (NMSA) was launched in 2020 following workshops that defined the problem statement as: "No comprehensive, internationally recognised skills standard for practitioners in metrology exists."

Practitioners may be full-time specialists or technologists with blended skill sets depending on elements of metrology.

This leads to:

- Variations in competency across industry, resulting in knowledge gaps and associated problems;
- Inconsistency in training and development solutions between providers;
- Industrial and scientific companies each developing their own solution for the competence of metrology staff, leading to duplicated effort and inconsistency;

- No standardised recognition of what a metrologist is or development paths for metrologists building their career; and
- Uncertainty when recruiting.

The initiative has been hosted by the Institute of Measurement and Control and its journal, *Precision*, has published the story so far.

The work was inspired by the BINDT certification scheme and recognises that NDE addressed similar issues in the past and has valuable experience in this journey.

The group is developing a skills framework, as outlined in Figure 12.

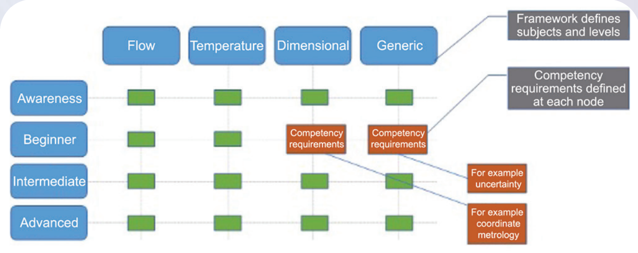

Figure 12. Concept for the metrology skills framework

Teams have been formed, with the core team and dimensional metrology taking the lead. There is a plan to deliver the framework in 2023 and material is already being produced.

As well as the NMSA learning from experience in NDE, there is now an opportunity for NDE to learn from the experience of the NMSA as both interconnected disciplines grapple with a more interconnected, interdisciplinary future.

Benefits of NDE 4.0 beyond maintaining structural integrity

Theme Chair: Nick Brierley, Diondo GmbH and Chair of the BINDT NDE 4.0 Group

Additive manufacturing: automation, optimisation, performance and integrity

Joe Grimwood, TWI

Additive manufacturing (AM) is a manufacturing technique that builds a component on a layer-by-layer basis. This has several potential advantages, including building near-net shape components, the potential to vary and tailor properties across different regions of a component and compatibility with highly automatable systems, consistent with Industry 4.0. The presentation gave a brief introduction into AM processes, before focusing on key techniques that can help facilitate optimised and automatable manufacturing cycles using AM.

One area of focus was in-line NDT techniques, including *in-situ* ultrasonic scanning and the use of complementary metal-oxide semiconductor (CMOS) cameras to monitor the melt pool during deposition (see Figure 13). These NDT techniques have the potential to allow for in-build corrective feedback and provide the opportunity to pause a deposition to allow for repair during the build sequence. This would help ensure better control of build parameters, giving rise to more consistent, predicable properties.

Other challenges in the application of AM material to highly automated manufactured cycles were discussed, including a limited understanding of the relationship between the process, resultant microstructure and corresponding impact on performance. This limits the structural integrity assurance of AM parts, and various activities to enhance this understanding, including modelling, destructive qualification testing and simulative environmental exposure, were discussed. The progress made in understanding and optimising build parameters to minimise the formation of gas pores and hot cracks was also discussed. Another specific area of interest is the grain solidification structure of AM materials, for example in nickel alloy 718. Changes in the build process or process parameters can noticeably change the grain structure, for example leading to coarse, columnar grain formation (see Figure 14). This has a corresponding effect on properties, for example leading to anisotropy in the mechanical strength.

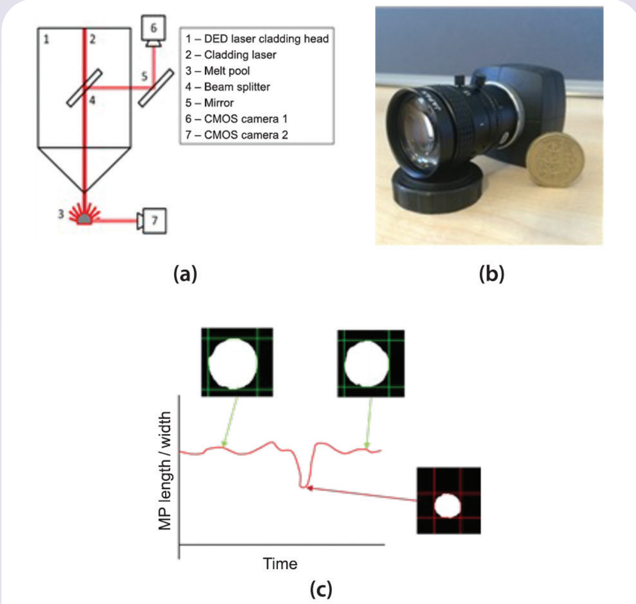

Figure 13. In-line melt pool monitoring using a CMOS camera showing: (a) monitoring set-up; (b) camera used for monitoring; and (c) example of corrective feedback to control melt pool size

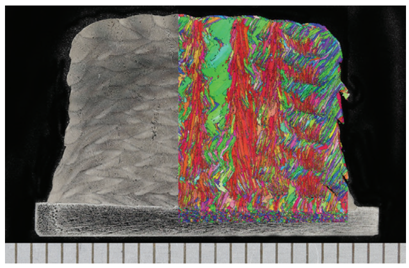

Figure 14. Micrograph in the etched condition with an electron backscattered diffraction (EBSD) map overlaid showing grain orientations from an alloy 718 AM material built using laser metal deposition

In summary, AM components have several advantages for some key applications, but it is vital that there is adequate control during build processes and a greater understanding of the effect of build parameters and component geometry on the resultant structural integrity and performance. In-line NDE techniques and other forms of characterisation and testing can help to make progress in these respective areas.

NDT as an enabler of circular economy

Marie Wells, MTC

In this talk, Marie explained that NDE has the potential to impact the environment in multiple ways. It can increase the quality and longevity of a product and decrease waste and raw material usage.

She also outlined the impact of NDE in each of the key areas shown in Figure 15:

- **In design,** as product validation, to aid in component reuse and the prevention of waste in product validation trials
- **In efficiency,** to provide analysis of components, machines and structures and to enable preventative maintenance, targeted repair/part replacement and the retrofitting of new technology to legacy machines
- **In processing techniques,** to optimise processes
- **In material management,** to increase trust in secondary materials. Validation of secondary/recycled materials:
  - Enables less material to be used
  - Potential to prevent downcycling.

  Validation of secondary parts:
  - Reuse is more energy efficient
  - Enables retention of material value.
- **In remanufacture,** to enable:
  - Confirmation of the integrity of the base material for remanufacture
  - May inform best remanufacturing techniques
  - Detection of the part needing replacement or upgrading.

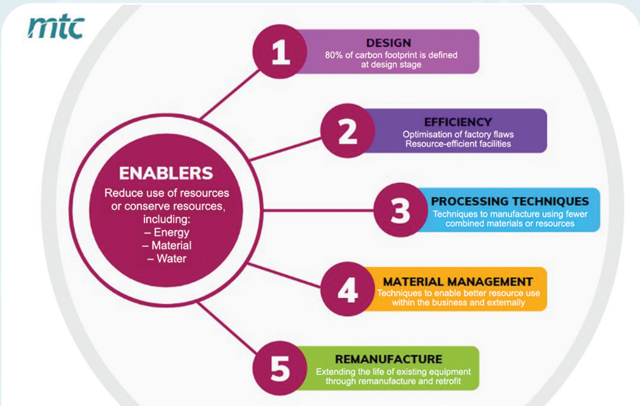

Figure 15. Key areas

The use of robotics for remote NDE in the offshore wind sector: remote NDE

Hamish MacDonald, Offshore Renewable Energy Catapult

Several workshop participants were already familiar with the other innovation centres within the overall Catapult Network (notably the High Value Manufacturing Catapult, of which the Manufacturing Technology Centre (MTC) is a part). To differentiate, the specific mission of the Offshore Renewable Energy (ORE) Catapult was stated. The 'scale of offshore wind' was then introduced, touting the colossal sizes of proposed modern offshore wind turbines, along with the worldwide pipeline of prospective wind farm areas further from shore. A significant challenge for the offshore wind sector is evident for a mix of assets: these next-generation turbines/wind farms and the initial generation are already through a considerable portion of their design life. With limited weather windows, the skills requirement gap and the overall cost of intervention offshore, the status quo will not be sustainable. The conventional operation and maintenance (O&M) philosophy needs to be advanced across the entire O&M process, from mission planning through to subsequent actions. A better and up-to-date understanding of the condition of all wind farm assets is essential to achieve informed decision-making. This will reduce reactive maintenance and allow for more effective intervention, prioritising human technicians for critical offshore activities.

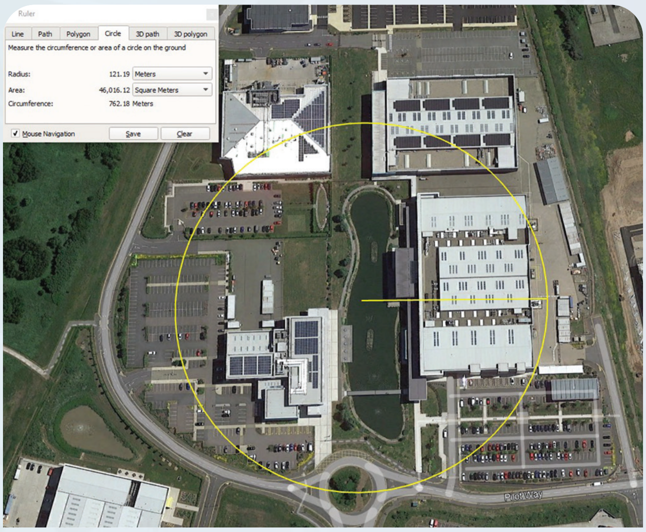

Figure 16. Overlay of the largest proposed wind turbine rotor diameter (to date) over the MTC campus

The potential influence of robotics and NDE was then detailed. Although already utilised for certain tasks on offshore wind farms, these robotic systems are primarily manually piloted remotely operated vehicles (ROVs) and drones, used for visual inspection subsea and topside, respectively. There is an ambition for robotics to take on an expanded role while also reducing the cost, health and safety (H&S) risk and associated emissions. Increasing the certainty of inspection and the remit of capabilities is desired, exploring other means of NDE and carrying out manipulative maintenance and repair duties. Fully unmanned operations for certain tasks are also a long-term goal, increasing levels of autonomy where appropriate and allowing for expanded weather windows.

Three recent ORE Catapult projects involving robotics and NDE were detailed. This included MIMRee, which explored end-to-end autonomous missions for wind turbine blade inspection, maintenance and repair, involving multiple robotic platforms and domains. Two novel methods of NDE within this project were discussed, including moving wind turbine blade assessment and laser profilometry. Another endeavour was the EchoBoltBUG project, which looked to combine EchoBolt's ultrasonic bolt inspection system and BladeBUG's crawling robot to assess the vast number of bolts in a wind turbine. Finally, the Amphibian robotic system from Innvotek was presented. This uses NDT methods for the assessment of wind turbine foundations both subsea and topside.

Several themes were summarised across these case studies, highlighting common technical, commercial and practical barriers to the future exploitation of robotic systems. De-risking and demonstration of innovative NDE payloads with robotic systems will be imperative to build trust and acceptance across a range of industry stakeholders. To assist in this, ORE Catapult is keen to expand its portfolio of practical testing capabilities that would be applicable across a range of Technology Readiness Levels (TRLs) and environmental domains.

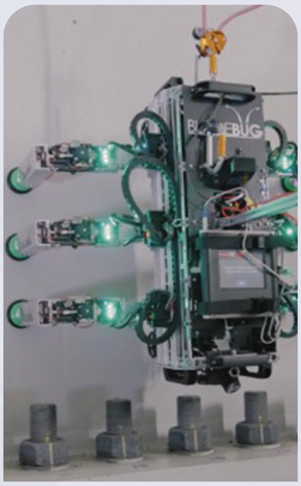

Figure 17. BladeBUG checking the torque of wind turbine tower bolts using EchoBolt's ultrasonic bolt inspection system

Risk-based asset management and the connection with NDE 4.0

Ujjwal Bharadwaj, TWI

Risk-based approaches in asset integrity management typically require the asset to be modelled as a system of constituent components in which a risk profile is developed for each component. In this context, a risk profile has two elements: the likelihood of failure of the component and the impact of such potential failure. The risk profile of an asset system is then shown on a risk matrix that depicts the individual risk profiles of the components in such a system. This approach helps asset operators to focus attention on high-risk components and take remedial actions.

On the one hand, NDE 4.0 has the potential to support the assessment of the likelihood of failure of a component that feeds into the risk profiling. On the other, in situations where NDE systems cannot be applied to all of the components equally due to economic or other reasons, risk profiling based on historical data or other sources can help to determine where such NDE systems should be cost-effectively installed to bring down the level of risk to within tolerable limits. Such an approach can support industry transition from an inspection and maintenance regime based on conventional methods to that based on NDE 4.0.

Case studies highlighting the above aspect were presented during the workshop. These will interest operators who have an existing system-wide NDE 4.0 feeding into risk assessments, as well as those looking to implement an appropriate level of NDE 4.0 based on their requirements. The approach delineated in the case studies can support operators in preparing a business case based on an optimal trade-off between the risk measured in monetary terms and the cost of risk mitigation via suitable NDE 4.0 coverage that focuses on high-risk components in their asset system.

Figure 18 depicts the key message from the case studies. Within an asset system, historical data is processed to determine susceptibility to failure (SOF); consequence of failure (COF) is calculated using a case-specific industry standard (MAC). SOF and COF for each component within the asset system is depicted on a risk matrix. The risk matrix can inform the inspection regime for the asset; the same matrix can support operators to determine where to install sensors (NDE 4.0 methods) based on a cost-risk optimisation calculation. These sensors can then provide real-time data that can be processed to dynamically update the risk matrix. In an advanced application, this set-up can be an analytical module in a system that is a digital twin of the asset.

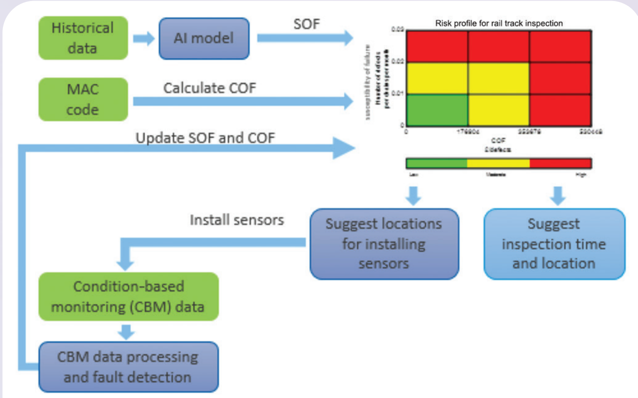

Figure 18. Risk-based asset management and NDE 4.0

Greater collaboration between NDE and communities such as metrology and materials

Theme Chair: Pete Loftus, RCNDE

Advances in metrology for Industry 4.0

Adam Thompson, Manufacturing Metrology Team, Faculty of Engineering, University of Nottingham, UK

Metrology, the science of measurement and its application, sits adjacent to NDT within the wider sphere of industrial verification. As we enter the era of Industry 4.0, measurement science has experienced a significant increase in research effort and industrial adoption. Notably, the wealth of manufacturing processes that require real-time in-line measurements has increased. Optical metrology has experienced a particular boom in manufacturing research. While contact-based approaches to measurement have been in service across industry for many years, optical technologies facilitate much faster cycle times and can allow for more in-depth inspections than are possible using contact methods. In this presentation, an overview of recent advances in metrology for Industry 4.0 was provided, focusing on developments in optical measurement technologies. Particularly, the challenges and opportunities presented by the integration of optical surface and coordinate measurement into the digital manufacturing processes that form the Industry 4.0 ecosystem were highlighted. Presenting the work from a recent review paper published by members of the Manufacturing Metrology Team at the University of Nottingham, as part of the Midlands Centre for Data-Driven Metrology (MCDDM), the state-of-the-art in hardware and software solutions for digital manufacturing metrology was noted. The move towards zero-defect manufacturing, within the context of sustainability, was also discussed. Applying the discussions to the world of NDT, the key challenges present in metrology research and development (R&D) today were presented, particularly relating to: measurement speed and data processing bottlenecks; geometric complexity, part size and surface texture; and user-dependent constraints, harsh environments and uncertainty evaluation. Following the review, the recent work being performed at the MCDDM was presented, noting the creation of a technology demonstrator that combines novel metrology developments and technologies. The demonstrator has been designed to feature optical coordinate and surface texture measurement in a measurement volume formed of a cube of 0.5 m × 0.5 m × 0.5 m, integrated machine learning and smart functionalities for data analysis, machine learning technologies for optimisation of scanning positions and high-level automation of the measurement pipeline. A digital representation of the demonstrator is presented in Figure 19.

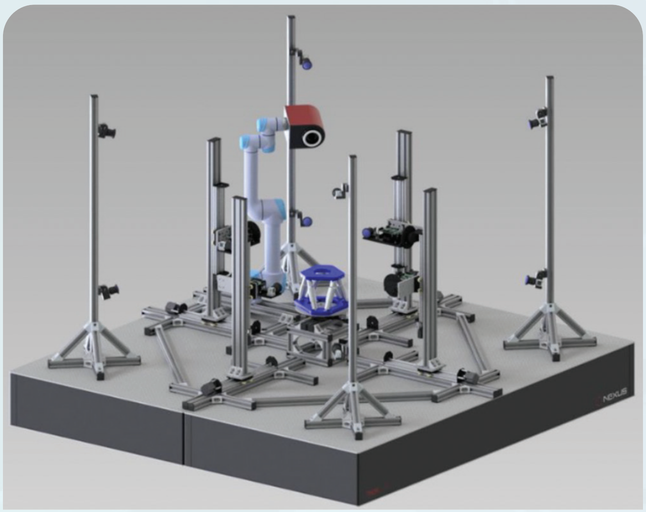

Figure 19. Computer-aided design (CAD) of the MCDDM demonstrator, featuring fringe projection and photogrammetry coordinate measurement systems and a surface texture measurement system

Materials 4.0: data-centric materials science and engineering

Iain Todd, Theme Lead – Materials Digitalisation, Henry Royce Institute and University of Sheffield

After introducing the Henry Royce Institute, Iain argued that materials development has suffered from a very long gestation period and aside from the exciting science we rarely consider resource availability, toxicity, scale-up, energy use, supply chain stability, manufacturability and recyclability – until it is too late.

Building on a landscape report published in July 2021, Iain outlined a transition from a trial-and-error process of material development to a model-based design process mirroring the transformation in the design process for physical products. He showed the way in which a digital materials design process would support the physical product lifecycle (see Figure 20). He highlighted some of the perceptions and barriers that have made this a slower journey and the progress that is now being made with pilot projects. The need for NDE to evolve in parallel with the materials development was brought out.

NDE experiences from the field: NDE 4.0 in the present

Theme Chair: Pete Loftus, RCNDE

Examples of how NDE 4.0 is delivering benefits in manufacturing

Tom Martin, JetSoft

In this talk, Tom outlined the way in which JetSoft is putting the principles of NDE 4.0 into practice.

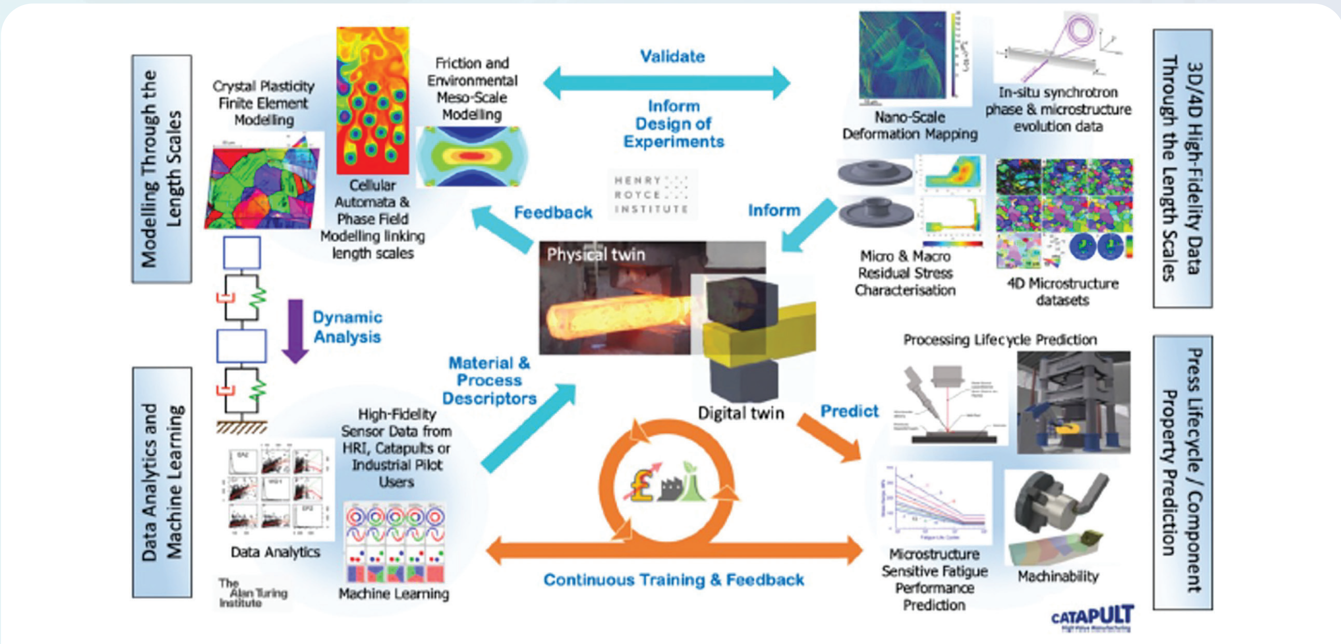

Figure 20. Doing more with less: a digital twin of state-of-the-art and emerging high-value manufacturing routes for high-integrity titanium alloy components

The company's OverSeer framework (see Figure 21):

- Aggregates and normalises NDT information across techniques and data formats
- Centralises data and provides easy-to-use tools to find and view inspections
- Automatically analyses data and collects results, notifying stakeholders
- Supplies business intelligence software to maximise the utilisation of testing information
- Enables the integration of inspection data with other systems and process information.

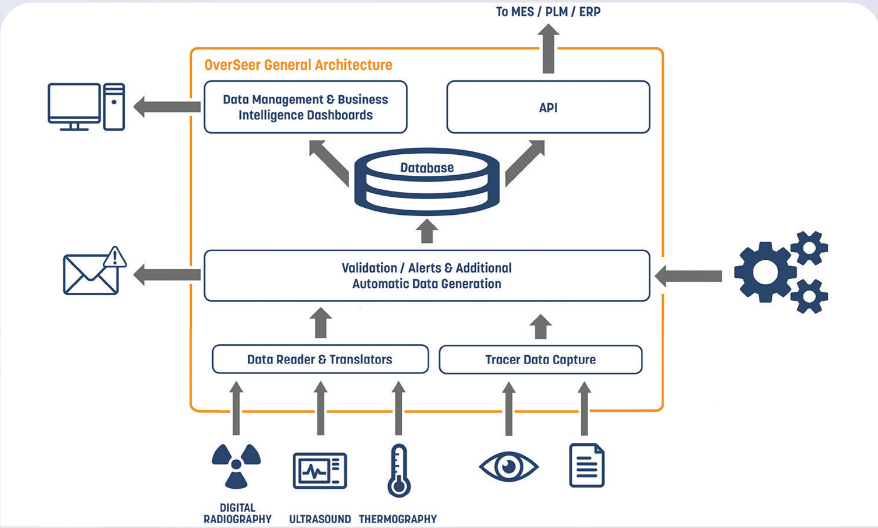

Figure 21. JetSoft's OverSeer framework

A key feature is automatic indication and causation detection. Mapping indications to the upstream process:

- Each possible indication has an ML model, taught using historic data (first deployed in 2018)
- Following each inspection, data is passed through each model, which gives a confidence level on that data containing an indication
- This confidence level is thresholded
- Results are stored and stakeholders are notified
- Business intelligence tools enable analysis of this data alongside manufacturing information for a detailed understanding of the indication cause
- This methodology has enabled scrap reduction, generating savings of >$2 million per annum and rising, with little input cost
- Empirical improvement of process models – delivering valuable IP.

Other roles are: automated process monitoring (see Figure 22) and material maximisation and automatic reapplication where NDE data directs downstream operations to reduce waste through adaptive processing.

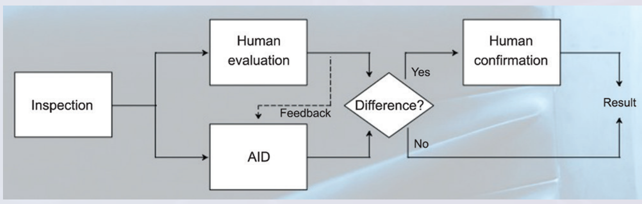

Figure 22. Automated process monitoring

Case studies on decision-making enabled by insights from continuous corrosion monitoring data

Philip Pakianathan, Jon Allin and Atilla Gajdasci, Permasense

This talk highlighted the contribution of continuous monitoring of corrosion in petrochemical plants. Permasense sensors are permanently in place, connected via wireless Highway Addressable Remote Transducer (HART) communications protocol systems with bespoke analytics to monitor, trend and alert on the data obtained. Case studies illustrated the impact to operations in European refineries. Challenges have included high-temperature operation, access and identifying high-risk placement positions.

Initiative to explore the state-of-the-art of AI-assisted corrosion detection in pipelines: where digital/intelligent methods are being used to benefit the inspection and CM purposes

Borja Martinez and Jürgen Moors, SPRINT Robotics

This talk introduced the SPRINT Robotics collaboration, which promotes robotics for inspection. This initiative has established an agreed workflow between the participants, reducing barriers to knowledge and data sharing around machine vision predictions for external corrosion in pipelines.

The initiative successfully created and shared a set of ~1300 pictures. 300 pictures were manually tagged by the asset owners looking only at general external corrosion on pipes. This allowed for the creation of evaluation metrics for each test set received, showing the difference between the manual tags and the predictions (see Figure 23).

Examples of the images collected, the manual and AI sentencing and decision-making were shared, the value of data pooling in this way was highlighted and some recommendations for the future were identified:

- The algorithms should be tailored to the needs of the asset operators as much as possible. The asset operators must therefore specify the desired characteristics of the predicted tags, such as shape (bounding box, polygon), the role the predicted tags are going to play in the asset operator's processes (detection, grading, trending, trigger for follow-up inspection and so on) and the desired way of recording.
- Additional detection tools may be needed to increase the performance of the AI predictions. This may include the use of segmentation masks to distinguish the targeted asset type from support structures and background.
- Recording and tagging of the images should be standardised.
- The number of tagged images should be increased significantly.

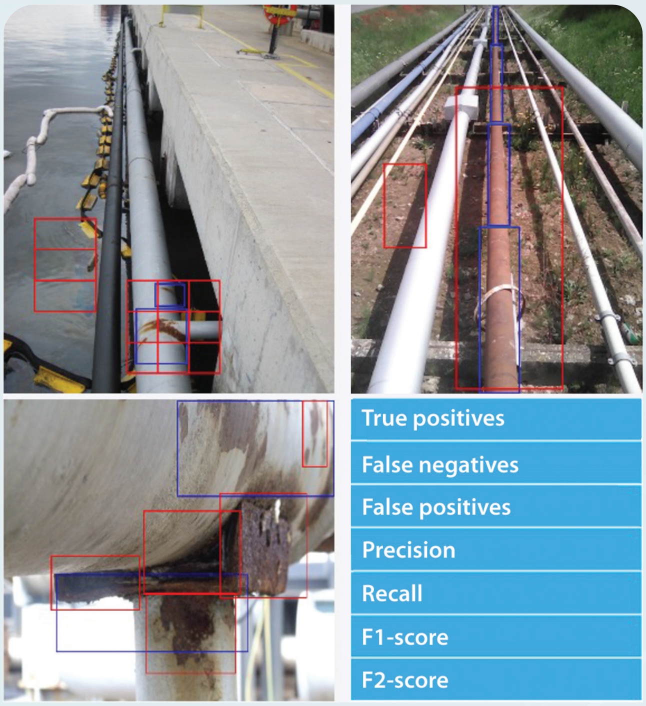

Figure 23. Evaluation metrics for each test set received show the difference between the manual tags and the predictions

Current research/work for potential future improvements

Theme Chair: Paul Wilcox, RCNDE

Summary of UK research for NDE/CM/SHM for Industry 4.0

Paul Wilcox, RCNDE

This talk drew together recent contributions by RCNDE, many of which have been outlined in more detail in other talks. It began with a reminder of the RCNDE modus operandi and the Centre's efforts to define a vision for the future of NDE that aligns with members' expectations.

RCNDE high-level vision documents:

- 2011:
  - Improved understanding, performance and reliability of NDE
  - Better integration of SI and NDE to enable a less conservative approach to plant design, operation and life extension
  - Minimisation/elimination of disruptive in-service NDE by adopting high-fidelity NDE at manufacture and during in-service structural health monitoring (SHM).
- 2016 updates:
  - NDE and monitoring to enable Industry 4.0 (*ie* NDE 4.0)
  - Removal of anticipated NDE requirements for 'clean coal' power generation.
- 2021-2023 update:
  - Currently in progress.

Figure 24 shows approaches to acquisition and analysis in NDE 4.0.

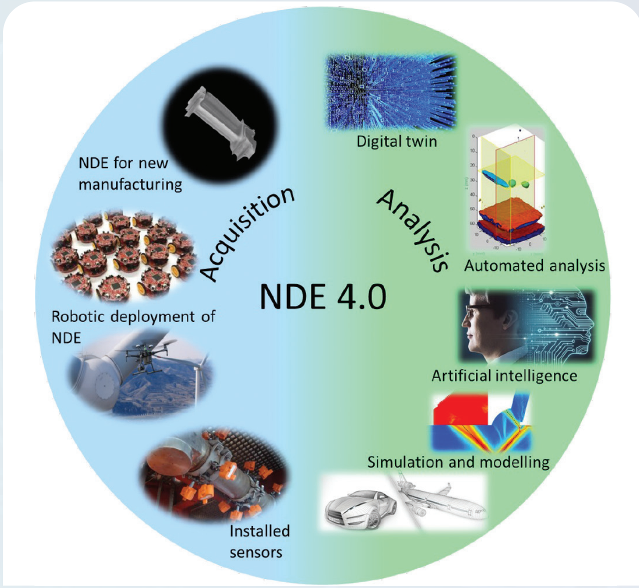

Figure 24. NDE 4.0: acquisition and analysis

Research examples highlighted were:

- Machine learning to suppress artefacts and improve sizing accuracy (University of Bristol)
- Microstructural characterisation at grain level (University of Nottingham) and in bulk (Imperial College London)
- Laser-induced phased array defect detection in extreme environments (University of Strathclyde)
- Permanently installed continuously monitored sensing for in-service monitoring (Imperial College London and University of Bristol).

The influence of RCNDE research in instigating emerging standards for the community, such as the common file format for full matrix capture, was also highlighted

Digital fusion of NDE and SHM via Industry 4.0: a researcher's shopping list

Fred Cegla, Imperial College London

This talk reviewed the author's understanding of what the commonly used term 'Industry 4.0' refers to and how the term 'NDE 4.0' can be viewed in that context. One of the core messages is that NDE 4.0 is a move towards fully digital ecosystems in which asset integrity assessment, inspection and monitoring needs to be performed. There are major prerequisites associated with this, namely the transformation of many specialist procedures that need human input into automated processes that are overseen by a human controller and the necessary software and hardware to implement these processes. At the same time, there are plenty of challenges that must be overcome. These are mainly associated with the supply chain of equipment providers, security engineering and skills and training of personnel.

The second part of the presentation was dedicated to the presentation of some of the research work that is or has recently been carried out in the NDE group at Imperial College London. The development of flexible, fast and powerful simulation techniques via finite elements (POGO FE) for the prediction of elastic wave signals from complex materials, as well as techniques to characterise complex grainy materials, was presented. Furthermore, progress towards building versatile NDE data acquisition systems for autonomous robots (SONOBOTICS) was presented, as well as work on improving measurements with permanently installed monitoring sensors in plants. The Imperial group is also researching novel data acquisition with coded excitation that is more suited to digital acquisition systems, requiring a minimum of analogue circuitry and no high-power electronics to send and receive ultrasonic signals from standard transducers. Finally, some research work on the statistical analysis of data from fleets of monitored sensors and the combination with other measurement data was presented.

Key conclusions were that because the current landscape is rather fragmented and there are recurring questions about the business case of applying certain techniques and the potential to integrate the data formats and content, it would be beneficial to have a unified ecosystem to which many players can contribute so that contribution and value-add can be properly attributed and directed. It is speculated that something like this might eventually appear just as there are competing software/hardware ecosystems (for example Apple, Android, Microsoft, etc, uni-/metaverses).

Laser ultrasonics for non-contact in-process NDE during manufacturing in extreme environments

Theodosia Stratoudaki, University of Strathclyde

Theodosia Stratoudaki spoke about the current and future challenges of NDE that stem from the requirements for the inspection of advanced materials, products and manufacturing processes. She presented these requirements from the point of view of in-process inspection of manufacturing, which often means inspection in extreme environments, with restricted access and addressing components of complex shapes. She brought up the example of AM and presented two case studies of laser-based ultrasound techniques that can address these challenges: laser-induced phased arrays (LIPA), developed at Strathclyde University (Dr Stratoudaki); and spatially resolved acoustic spectroscopy (SRAS), developed at the University of Nottingham (Professor Matt Clark). Both of these techniques use lasers to generate and detect ultrasound. As a result, they are non-contact (remote) and couplant-free.

In the case of LIPA, Theodosia presented 2D and 3D ultrasonic TFM imaging of various additively manufactured metal components (for example aluminium and titanium and steel alloys) on as-built or rough surfaces and demonstrated how LIPA inspection has the required resolution to detect and characterise the bulk of additively manufactured components in depths as deep as 25 mm below the laser scanned surface. She then mentioned that for in-process inspection the challenge is to reach a high enough speed of inspection to address the throughput of metal deposition. She presented the plans for adaptive LIPAs and the framework of the current research at Strathclyde University, which includes robotic delivery of the technique for automation and integration with the wire arc welding and wire arc additive manufacturing processes (Dr Charles MacLeod).

Regarding the case study of SRAS, the technique provides material characterisation of the component's surface, including grain size and orientation. Several examples were presented from SRAS scans on large components (tens of cm), whereas the inspection size limit is only set by the scanning strategy capabilities. Material characterisation of as-built components was also presented. Currently, SRAS is being further developed to address the requirements of selective laser melting additive manufacturing (SLM AM) and an SRAS inspection cell is being built and adapted as part of an SLM AM system. The system is designed to comply with health and safety requirements of the manufacturing environment.

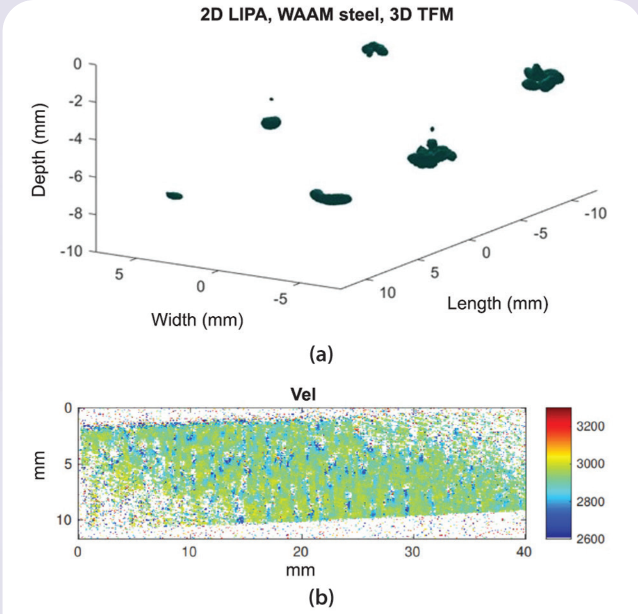

Figure 25. (a) Volumetric TFM images from a steel wire arc additively manufactured sample with flat-bottomed holes, using ultrasonic data acquired by 2D LIPAs; and (b) SRAS material characterisation (surface acoustic velocity map) from the surface of an as-deposited aluminium SLM AM component

Model-based definition-driven digital thread for NDT inspection

Nathanael Turner, MTC

This talk presented an overview of the role of model-based definition within Industry 4.0 applications. A summary of examples was given from some recent MTC projects that focused on the use of the quality information framework (QIF) to achieve Industry 4.0 benefits within the world of dimensional metrology, see Figures 26 and 27. The key points raised were the potential for this framework to be expanded to include various other types of quality data, including that from NDT/CM and SHM.

Firstly, the requirements met by the QIF were highlighted, including:

- Interoperability/open data standards
- Single authority model, which can be updated on the fly
- Human- and machine-readable format
- Unique IDs support data and part traceability.

Secondly, the outstanding requirements sought to enable the inclusion of NDT/CM/SHM data were summarised, including:

- The specification of volumetric or ancillary features to aid current inspection or enable automated inspection
- A universal or consistent framework for applying integrity requirements, analogous to the geometric dimensioning and tolerancing (GD&T) scheme, such that they can be machine readable
- The extension of scope beyond final inspection, *ie* in-service, end-of-life inspection considerations.

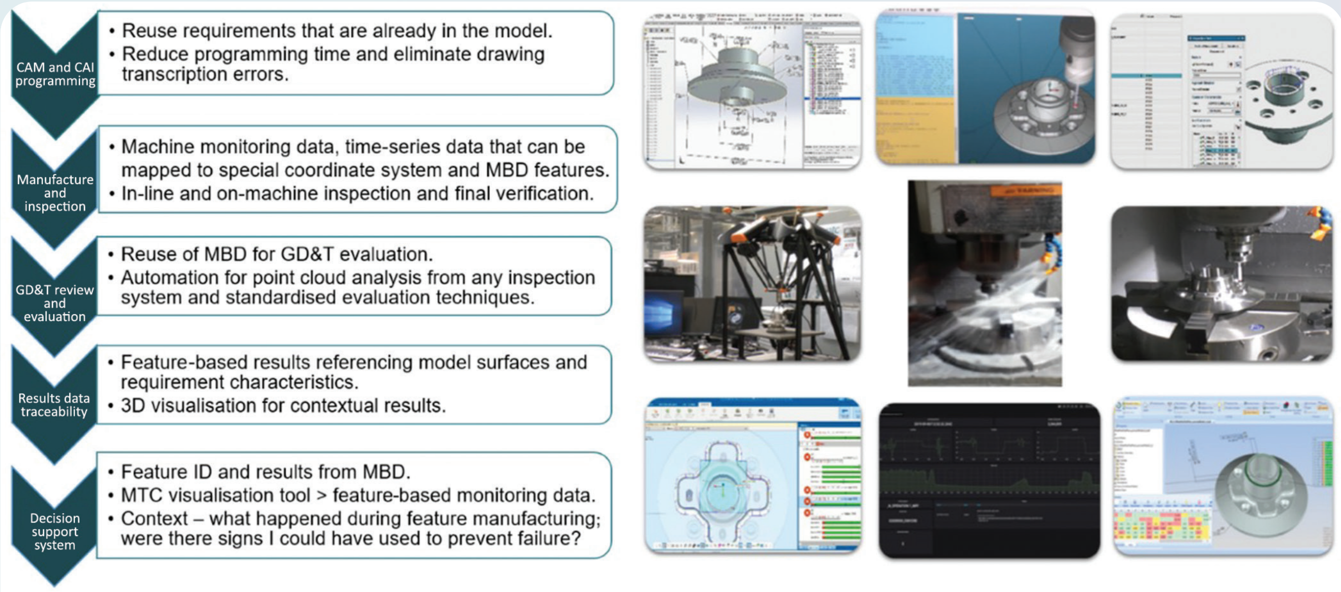

Figure 26. Images illustrating the process flow covered by the digital thread in the MTC project IIIQ-D

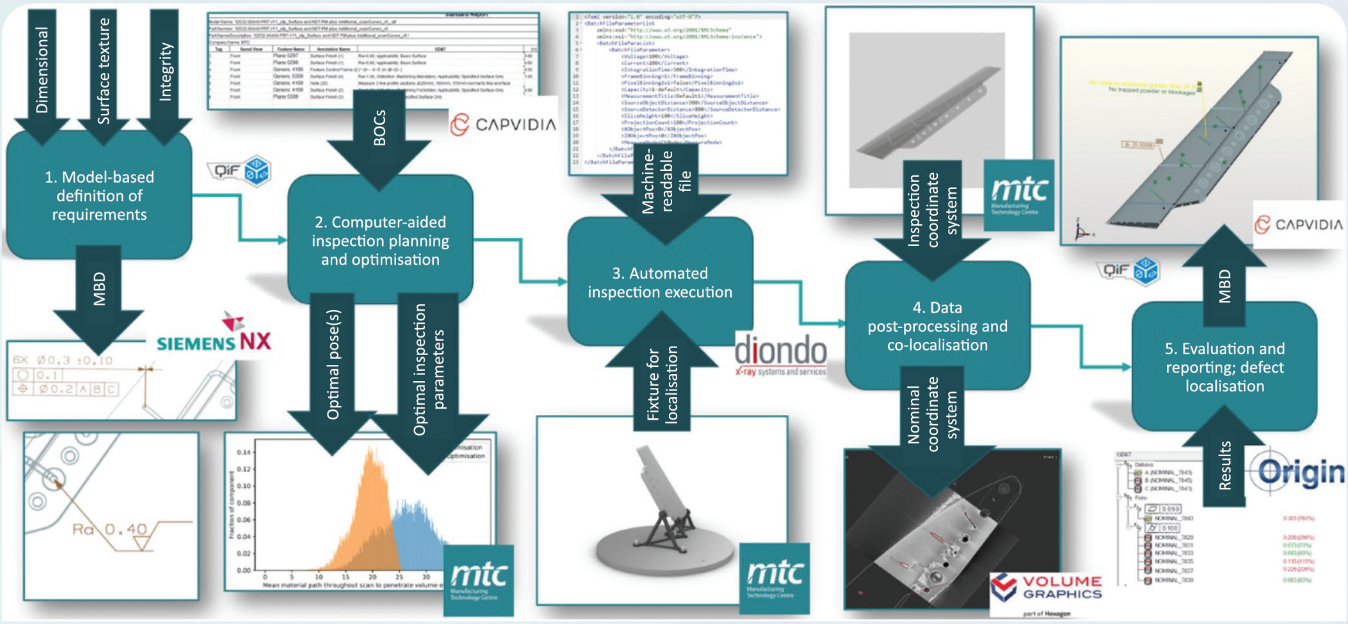

Figure 27. Overview of the MBD driven digital thread workflow followed in the DIRECT project at the MTC

The last part of the talk focused on a project by the MTC that demonstrated the potential benefits of the QIF for NDT. The main example was based around the optimisation of the X-ray computed tomography (XCT) inspection of an AM component from inspection requirements defined in the model and linked to features of the part.

Breakout groups and panel discussions

The workshop participants were divided into small groups to encourage discussion and were posed questions by a facilitator.

At the end of each breakout period, a panel of facilitators provided feedback to the whole group. In this way, the consensus around the challenges was assured. The following is a condensed output in bullet point form from the overall process.

1. Challenges and opportunities from improved NDE/CM/SHM capability

- Drag of poorly understood legacy process and "we have always done this" thinking acknowledged; also, diversity of terminology can hinder communication with other disciplines
- The cost of data storage was also highlighted
- Opportunities of designing-in inspection from the outset
- Business cases are often hard to articulate
- Resourcing is a challenge and opportunity, as is interdisciplinary consistency in the structure of education and best practice
- Demographics are a major concern as there appears to be a need to train a cadre of new NDT engineers in legacy systems at just the time we have emerging methods and skills we will need them to adapt to
- Virtual training presents an opportunity
- Probabilistic approaches provide opportunity

- Understanding the manufacturing process and through-life operation helps to identify opportunities for reduced but optimised inspection
- Acceptance/validation/qualification of AI is a generic challenge
- Standardising data formats supports interoperability/agility/improvement
- Regulators and original equipment manufacturers (OEMs) need to drive the changes
- AI needs to cope with non-standard failure modes
- New sensor solutions may address new failure modes
- Need to link between defect and system level failure, for example impact of composite waviness and fatigue life
- There is kudos in being an early adopter but a learning curve too
- Risk of overkill?

2. NDE/CM/SHM for self-verifying assets? On-the-fly SI calculations based on digital twins

- OK for standard aspects but if the failure mode is unexpected and not included in the model it will not work
- Competent people (SI, sensors, software and so on) need to be involved at the right stages
- Need to understand the limits of acceptability
- Need to be able to adapt to emerging failure modes
- The DTs/structural integrity management system need awareness of the plant conditions, for example loads and temperatures as well as the material response
- Needs to be risk-based
- Accountability needs to be clear
- Changes of plant ownership will require changes in data ownership.

3. Requirements and barriers for the use of AI/ML in the NDE/CM/SHM SI process

- Availability of data for training; quality of data and metadata, including the extent to which all possibilities are covered in the datasets – defect data may need to be simulated or read across from analogous situations
- Lack of understanding
- Being able to trust the AI output is key and the consensus was that this needs to be proven in some way; must be able to explain how the system is arriving at decisions
- Managing expectations of the community; a framework to develop trust was widely viewed as a key requirement
- Ensure that we learn from other applications of AI/ML, for example self-driving cars
- Managing human responses to the system behaviour
- Uncertainty quantification in outputs is important
- Perception that jobs will be taken away
- Use AI to present human operators with options
- Strategy for data collection is important to gather only what is needed
- Regulatory input to the validation methodology will be important
- Many algorithms are available
- Public domain test datasets are needed
- Confidentiality – dealing with proprietary data.

4. Communicating: persuading industry of requirements on NDE/CM/SHM to gain commitment

- BINDT/certification
- Formalise requirements
- Standards and good practice
- Transparency
- Explainable/simple
- Elevator pitch
- Communication has a cost
- Cost/benefit understanding is key to persuading anyone to change
- Need to sell the technique/skills/process changes and so on
- Case studies showing where NDE 4.0 has made an impact would help
- Why should we push this? People will realise the benefits eventually anyway
- There will be differences in approach between industries, applications and techniques.

5. Interpretation of NDE/CM/SHM information. Better understanding by users. Dissemination

Manufacturing or service inspection provide different contexts and the answers may be different. However, the following suggestions were made for helping the data user achieve a better understanding:

- Communication of capability, for example capability guide
- Understand the use that will be made of the data
- Be clear if this is a pass/fail or quantitative capability
- Articulate the level of confidence in the data
- Different data users (and software tools) need the data presented in different ways, for example virtual/augmented reality tools help with visualisation
- Standardised forms of data presentation will help
- Part ID/QR codes, etc, for a key part of the metadata.

6. Who is taking the initiative? Should this change? Is there an economic benefit that will ultimately drive it? Do we need an intervention?

One view was that we have industrial pull and we have academic champion, so nothing more is needed.

Other points included:

- We want to see a range of approaches considered – cannot pick a winner
- Successful implementations could be rewarded and encourage others
- Different Industry 4.0 initiatives are happening – something is needed to link these and ensure read-across of standards, for example in data formats
- A library of case studies to help companies make the business case to invest
- Through-life continuity is important to facilitate the use of production and early life data
- The insurer needs to be engaged in the change process to gain acceptance of new methods.

7. Improved asset performance (through-life)

Deployed asset management systems:

- Need to accommodate actual operating conditions, multiple stakeholders, supply chain relationships, traceability and auditability; as well as optimising the current equipment/plant, they also need to inform the next generation
- Require clear metrics and technical and economic cases to underpin investment
- Must be resilient against life extension/modifications/upgrades/reuse and unforeseen degradation.

Digital twins were seen to have the potential to help with all of these requirements and the integrity of the digital twin through-life will be critical to delivering that potential.

8. More efficient production and design/make of new products

Cashing in NDE 4.0 in this context was thought to require:

- Embedding techniques into process and product design
- Bringing all of the information together to make decisions in manufacture and service
- The ability to relate defects to process parameters.

These would deliver increased efficiency and reduce scrappage and more flexible concessions based on data and evidence.

These in-turn would require:

- Compatibility of data in a shop-floor context
- Common APIs; fusing 100% inspection and statistical process control data; design for inspection and the challenge of showing cost benefit; and a standard way to specify functional NDE requirements
- May need regulatory input for societal benefit as the designer/manufacturer is not incentivised to optimise through-life performance – when is a digital twin needed/justified?

9. Better/faster/cheaper NDE/CM/SHM (incremental improvement, includes less frequent)

- It was recognised that solutions need to be both affordable and cost-effective but that judging this requires credible cost/benefit analysis
- The need to understand the requirements was highlighted, including applicable standards, repeatability and traceability
- Confidence in the decision-making was seen as a key part of the benefit
- Skills, training and certification are key even in an automated world
- Ownership of data needs to be clear to avoid longer term costs.

10. Efficient quality control for customised products, for example additively manufactured products

Drivers/aspects to be considered for QC:

- Desired lifetime for the component
- Engineering standards
- Customer specifications
- Sample or 100%
- Regulatory acceptance
- Safety-critical components
- Value in business terms
- Toolbox – customised QC.

Aspects to possibly include for QC:

- Verified model
- Characteristics to find/miss
- Acceptance criteria (standardisation?)
- Training/competence
- Physical condition
- Material properties
- Probability of detection (POD)
- Root cause analysis
- Transportation
- Repeatability
- Use of digital twins
- Corrective action
- Documentation.

How should the QC aspects be undertaken and by whom?

- An unbiased third party
- Significance of findings
- Online re-evaluation if component use changes
- Stamping/passport certification.

How should the information be processed, stored and used?

- In line with appropriate standards
- A common approach as far as possible.

How should/could the information be used more generally?

- An overarching standards body?
- More sharing of data (cost sharing)
- Commercial issues?
- Feedback to R&D
- Corrective action.

11. Reduced need for personnel being in harm's way/travelling

- Installed sensors – minimise the need to deploy people and provide better trending
- Robotic deployment and autonomy
- Trending data – better prediction/confidence therefore defer inspections/outages
- Separate analysis from acquisition, with an expert at HQ – is this demotivating for technicians? Expert is isolated
- Remote NDE techniques
- Remote operation of kit
- A material that is thermally insulating but transmits ultrasound so that inspection can take place through thermal insulation
- Smarter use of data fusion – mining
- Digitisation of data
- More universal scanning systems (kits) and greater autonomy.

12. Efficient quality control for decentralised production

- Traceability – ensuring the measurements are correct and reproducible was the key point raised
- Standardised protocols for processes and procedures (NDT, CAD models)
- Communication (understanding what needs to be communicated) and protocols (more chance of machines communicating effectively than humans!)
- Authentication of link back to item (for example serial number, original design), fingerprinting (for example embedding or using NDT)
- Diversity of supply (related to cost and availability)
- Minimum configurations for acceptance
- Same audit trail and characterise raw materials
- Calibration traceable so comparison can be made and commonality ensured
- Might need to be adaptive for in-service components depending on the service environment → smart system
- Need to learn from experience
- Need a back-up communication system
- Understand thresholds around conditions, for example adhesives
- Safety, *ie* data stored in a safe manner
- Subjectivity – when is an acceptable deviation OK? This depends on criticality.

Requirements lists

The following requirements have been derived from the presentations during the workshop, the breakout and panel discussions and feedback to BINDT after the meeting. They are presented as outcomes from the meeting, which the participants had the opportunity to challenge and which, therefore, represent a reasonable statement of the industry view.

The taxonomy used is consistent with the BINDT NDE 4.0 Group roadmap approach but has been adjusted to capture all of the material under the following requirement headings:

- Industry 4.0 and NDE 4.0 concept and delivering improvement
- Workforce skills and human factors
- Improved lifecycle management of in-service product; manufacturing and process plant; and infrastructure assets
- Improved manufacturing-specific requirements, including inspection of the part during manufacture and new product introduction
- Better, faster, cheaper NDE (optimising the delivery of NDE/CM/SHM)
- Reduced need for personnel in harm's way
- Generic NDE 4.0 technologies
- Generic system attributes
- Standards.

Industry 4.0 and NDE 4.0 concept and delivering improvement

At first glance, there appears to be nothing to stop the widespread adoption of NDE 4.0 approaches, particularly as its deployment will be evolutionary in most businesses. The main challenges appeared to be those of producing the future vision, optimisation and mindset. However, in addition to specific technology and methodology requirements listed later, there were several generic considerations that were highlighted:

- There is a chain of impact though materials, parts, processes, plant and equipment, fleet/factory, company and economy to the global environment; the higher up this chain we intervene with improvements, the greater the impact.
- Resilience of the system of systems is a key goal.
- Linking all relevant aspects relating to asset management in a digital form is the way things need to be progressed.
- Publicly accessible benchmarks should be used to validate and verify novel approaches used in NDE 4.0.
- The goal is not necessarily always a perfect sensor; if multiple measurements can be undertaken, robust conclusions may be possible through trending, data fusion, digital twins and so on.
- It is difficult, if not impossible, to predict what will emerge from NDE 4.0. As a professional body, it is important that BINDT does not focus in too much detail on the methodologies themselves, but rather on the overarching commonalities that distinguish '4.0 methods' from their predecessors and what is needed to ensure that output is robust. Unfortunately, it will be less about exciting new technologies and predominantly about ensuring that all data is collated in a way that is machine readable, archived (in such a way that data is easily found) and easily communicated from one system to another. Communication and interpretation of data will be the cornerstone of NDE 4.0.
- Education/promotion for the wider engineering community will help generate pull.
- Regulatory pull will be generated by showing regulators the contribution new technology can make to safety.
- Business models of asset owners impact the drivers for NDE, etc, for example asset ownership or maintenance passing from the operator to the supplier or third party.
- Business case development case studies.
- A view was expressed that too much complexity has crept into the subject and an effort in simplification is needed; this begins with clarity over the full process to avoid sub-optimisation.
- There were numerous pleas to learn as much as possible from other sectors.

Workforce skills and human factors

An industry skills strategy is needed to account for approaching demographic change along with emerging skills profile needs, with:

- Suitably skilled personnel to develop, maintain and use NDE 4.0 technologies
- A certification scheme with qualifications such as Levels 1-3
  - Recognition of existing qualifications – gap analysis to NDE 4.0
- The ability to respond to a skills gap as technology develops
- The ability to respond in the face of new demands
- The ability to maintain skills when automation has reduced direct experience of the process
- The ability to assess and demonstrate relevant skills and competence
- BINDT to continue to support up-to-date skills training and certification.

The community in NDE has a distinct and helpful identity that needs to be sustained, developed and replicated across the broader CM and SHM domains.

Steps should be taken to reduce the frequency of human error, whether this is by easing the task through automation/decision support or by procedure.

Improved lifecycle management of in-service product; manufacturing and process plant; and infrastructure assets

- Improving inspection strategy, optimising operational envelope and understanding the relative value of manufacturing process control *versus* in-service monitoring
- Adaptive monitoring systems to respond to degradation and emerging failure mechanisms – challenge: keeping the model (and sensing) up to date with emerging degradation mechanisms
- Links to plant and enterprise databases (for example MAXIMO, SAP)
- Combine models and plant data and NDE:
  - Fit the plant with transducers that measure the key structural parameters
  - Feed these parameters (and original plant data such as material data) into a structural model that can be used to assess fatigue life
  - At the very least, better plant information can start to predict when and where fatigue cracking is likely to be a problem and periodic inspection can be scheduled more precisely
- Autonomous operation across extended asset fleets
- Covering large areas/identifying high-risk sites for continuous monitoring or detailed inspection
- Robotic access for reduced cost, improved consistency and operator safety.

Improved manufacturing-specific requirements, including inspection of the part during manufacture and new product introduction

- Integration with dimensional inspection
- In-process monitoring: high-temperature capable instrumentation; remote characterisation of microstructure, process parameters and defect detection
- QC for customised products, for example additive manufacturing
- QC for low volumes and rare defects.

Challenges:

- Temperature
- Surface condition
- Access difficulties, for example small inspection area (from less than 1 mm to ~3 mm)
- Environment: dust, spray and so on
- Must not compromise the product, for example contaminate surface, cause local cooling and so on
- Inspection speed (and analysis) needs to match production speed.

Better, faster, cheaper NDE (optimising the delivery of NDE/CM/SHM)

While none of the speakers specifically highlighted a need to reduce costs and timescales as a key motivator, most of the developments listed will deliver improvements in speed of operation, overall operating costs or better lifecycle management.

Reduced need for personnel in harm's way

This requires remote sensing, harsh environment robotics and sensing, harsh environment communications or autonomous operation.

Challenges for robots:

- Autonomy
- Working in harsh environments: hot, radioactive, chemically aggressive, vibration and so on
- Power supply and communications
- Coupling to the target; for example, if it is an ultrasonic inspection, how do you couple the ultrasound?

Generic NDE 4.0 technologies

- Robotics, AUVs and crawlers
- Digital twins
- Cloud data storage supporting diverse shared ownership and access models
- Data visualisation to support human decision-making
- Automated defect recognition (ADR) and sentencing and AI/ML
- Sentencing using models (digital twins) to reject artefacts
- Laser scanning and photogrammetry
- Data analytics and prognostics
- Machine learning and AI adapted to very small training datasets and high-criticality decisions
- Non-destructive materials characterisation
- Enhanced connectivity, for example 5G.

Generic system attributes

- A unified ecosystem to which many players can contribute so that contribution and value-add can be properly attributed and directed
- Adaptive monitoring systems
- Optimised mix of monitoring and inspection
- Acquire sufficient data, better data and data with appropriate metadata
- A digital twin that allows all to integrate all NDE data, not a twin per NDE technology or application
- Systems designed with inspection and monitoring in mind.

Interoperability of systems, software and people:

- Interoperable data formats for data of all types
- Data held in self-describing formats controlled by open standards
- Transducers also need to be self-describing, IEEE 1451/TEDS
- More modular NDE software, for example much simpler integration between the robot moving the probe and the software analysing the image from the ultrasonic phased array
- Communications in distributed architectures, remote locations, presence of electromagnetic interference (EMI) and so on
- Requirements that are met by the QIF, including:
  - Interoperability/open data standards
  - Single authority model that can be updated on the fly
  - Human and machine-readable format
  - Unique IDs and part-marking support data and part traceability.

Standards

There were pleas to develop standards in several areas:

- A framework for validating AI models
- An open data standard, which may be used to connect the various NDE 4.0 elements
- Template data sharing/pooling agreements/guidance/case studies
- Specification of volumetric or ancillary features to aid current inspection or enable automated inspection
- Universal or consistent framework for applying integrity requirements; analogous to the geometric dimensioning and tolerancing scheme such that they can be machine readable
- Extension of scope beyond final inspection, for example in-service end-of-life inspection considerations
- Data format and interface standards
- Design for inspection guidance.

Summary and next steps

The Executive Summary that opens the report provides a high-level summary of these requirements.

There was a determination amongst the organising committee and attendees to build on the work reported here to help deliver on the potential provided by NDE 4.0 concepts. One way to do that is simply for readers to reference this document in submissions for research funding, investment, etc, as evidence of the industry view. Another is to revisit the BINDT NDE 4.0 roadmap to ensure that the points raised in the workshop are captured there. The Technical Advisory Team agreed to reconvene once the report is published to discuss other mechanisms to build on the workshop outcome.

NDE 4.0 has clear international momentum and purpose. Here, we have drawn together some of the key things that need to be delivered to make that vision a reality. Between the sponsoring and participating organisations, we have all the ingredients to make them happen and the passion to pursue that goal.

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