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Advances in the UK Toward NDE 4.0

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ABSTRACT

In the UK, the NDE community is making a coordinated effort to underpin and enable the full benefits of the large-scale trend toward comprehensive digitalization and automation of industrial processes and assets, frequently referred to as "Industry 4.0". Certain facets of what is now considered to be NDE 4.0 have been the subject of research for some time and have already gained industrial traction, while others are quite new, with unexplored potential and pitfalls. However, in these areas there is scope for learning from progress in fields outside of, but related to, NDE such as dimensional metrology. This paper reviews progress to date based on UK activities, considers some planned and potential research tasks in this domain, and highlights the major challenges the NDE community must tackle. In particular, as interoperability and data reuse are key features of Industry 4.0 practices, international and cross-domain efforts on data format standardization are needed. It is clear that, without the NDE community stepping up to the challenge, much of Industry 4.0 cannot be realized; yet if the NDE 4.0 vision is implemented comprehensively, NDE has the potential to become more capable, more valuable, and therefore more highly valued.

KEYWORDS
Industry 4.0; digitalization; traceability; data analytics; digital twin; data formats; standardization; automation; structural health monitoring; condition monitoring; augmented reality; training

1. Introduction

In recent years, there has been an accelerating trend toward comprehensive digitalization and connectivity of industrial processes and assets, with associated increases in the use of technologies such as robotics, simulation, machine learning and cloud computing. Given the potential productivity and efficiency improvements, this trend has been embedded in the strategies of companies and governments [1], and is frequently referred to as "Industry 4.0". Of course, this also extends to the world of Nondestructive Evaluation – hence "NDE 4.0" [2] – which is also itself an enabler of wider Industry 4.0 practices, given that inspection is a major contributor to a manufacturing organization's data, capturing the quality of components in-process (during manufacture), in-line (between manufacturing stages), end of line (when production is complete) and

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in-service (when product is/has been in use – including life extension, for example), potentially up to end-of-life scrappage/recycling.

In contrast to e.g. the logistics sector, the NDE world has not been one of the fastest industrial communities to start adopting Industry 4.0 practices, probably due to regulatory constraints in safety-critical industries, partially explaining the multitude of industrial NDE processes that have not changed in decades. Nonetheless, especially in the context of the widespread use of somewhat dated (e.g. paper-based) processes at present, a move toward fully digital practices and connected technologies is expected to yield significant benefits. This applies both to NDE practitioners and owners/operators of safety-critical assets. For example, the former can expect to be able to consult technique instructions, historic data and off-site expertise via Augmented Reality (AR) while in the midst of conducting an in-service inspection; the latter can expect to be able to have a comprehensive and up-to-date representation of their asset's condition (a "Digital Twin" of product/process/facility – a virtual embodiment based on data from the physical instance, used to support decisions to be implemented in the physical world) available via any internet-connected tablet, enabling improved (and indeed automated) decision making about operating parameters and maintenance.

The UK Research Center in Nondestructive Evaluation (RCNDE) [3] has described an ambitious vision of the ultimate realization of NDE 4.0 for a given asset: Automated Nondestructive Integrity Verification (ANDIV). Figure 1(a) indicates how NDE currently fits into the overall assessment process of a typical engineering asset. Here, human roles feature throughout an inspection process, not only in the manual acquisition and interpretation of NDE data, but also in the decision making on part acceptance (stress/structural engineer) and conformance to the specification based on the NDE data (NDE engineer). Instead,

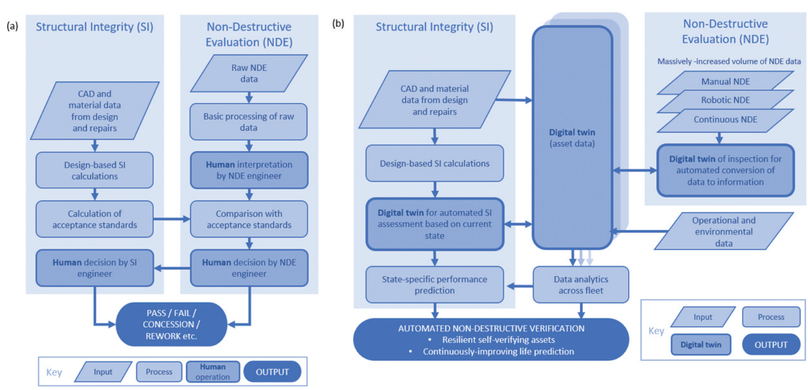

Figure 1. Schematic illustration of (a) the current standard NDE decision-making process about the fitness for purpose of an asset, compared with (b) the potential future state – Automated Nondestructive Integrity Verification (ANDIV) – where human inputs are moved to the process-design and verification stages.

in the ANDIV model presented in Figure 1(b) the human roles are all but removed. Fitness-for-purpose verification is fully automated and continuous, based on operational loads/conditions data acquired through networked sensors complementing NDE data. The data supports a comprehensive Digital Twin of the asset, with data analytics providing continuously improving life-prediction accuracy, and, potentially, on-the-fly performance modelling in place of design-stage specifications of defect acceptance criteria. ANDIV incorporates inputs from the NDE, structural integrity, design, manufacturing, materials science and regulation communities. This provides an interconnected process for continuous automated verification, which reduces the overall risk and cost while increasing confidence and performance. Human input will still be present but it will be focused on the earlier process-design and verification stages.

The NDE world indisputably has some way to go to reach the full potential required to support the ANDIV vision of its place in Industry 4.0. However, some activities of the past years, such as work on advanced robotic inspection [4], will contribute directly to this, without, at the time, having been considered to be part of a wider Industry 4.0 digitalization effort. Additionally, there has been a growing awareness of the need for a concerted effort in this area [5], in some cases giving rise to concrete initial research activities.

The comprehensive use of digital tools will lead to a closer alignment between the NDE world and related fields, such as those concerned with other aspects of quality control. It is therefore worth noting that some of these related fields have made substantial progress to date in moving toward Industry 4.0, so there is likely to be scope for the NDE community to learn and borrow from colleagues, such as in dimensional metrology.

There is much work still to be done and some challenges facing the NDE community on this journey are already identifiable. For example, the move toward greater hardware and software interoperability not only requires the further development of standards for data exchange, but also has commercial and cultural implications for the NDE supply chain. Additionally, the greater use of algorithms for processing and evaluating data, especially those based on machine learning (ML)/artificial intelligence (AI), raises major challenges in relation to algorithm qualification/validation and the role and training of NDE personnel.

This paper will expand on these subjects, examining some of the progress to date in the UK toward NDE 4.0, highlighting ongoing and planned activities, before a discussion focused on challenges, and conclusions.

2. Advances to Date in the UK

2.1. Completed Activities Directly Contributing to NDE 4.0

The High Value Manufacturing Catapult (HVMC) [6] is a network of applied research and development centres initiated in and supported since 2012 by the

UK government as a key part of its industrial strategy [7]. Within this the Digital Engineering division of the Manufacturing Technology Center (MTC) has been at the forefront of UK efforts on Industry 4.0, and is making progress on NDE 4.0, primarily via its Metrology and Nondestructive Testing group.

2.1.1. DISMAN

The most directly relevant completed research project is called DISMAN (Digital Inspection for Smart Manufacturing). The first objective of this project was to map the key pieces of data associated with the NDE process to the benefits that could be realized through digitalization and access to that data through the manufacturing process and product lifecycle. Such considerations are especially relevant to traditional, manual inspections by techniques such as magnetic particle inspection (MPI), where a detailed record of the inspection is rarely obtained/retained. The second objective was to create an NDE 4.0 demonstrator based on an industrial use case.

An industry survey was conducted to assess the current level of digitalization, the aspirations and potential for improvement in this area within the UK manufacturing industry. Many respondents expressed an interest in greater use of inspection data for improvements to the manufacturing process and understanding their key process variables (KPVs). However, all respondents used paper-based reporting to track parts through the manufacturing process, with stamps and wet signatures for approvals. Digital inspection reports were often used to record the outcome of the inspection but rarely revisited after the inspection process. Key challenges identified for making progress toward NDE 4.0 included that proprietary formats for raw inspection data limit data access beyond supplier-specific software, as well as high data-volume storage requirements, with many discarding the raw inspection data if retention is not explicitly required. Interestingly, a cultural barrier was also highlighted: the fact that NDE is viewed as a "non-value added" process, making gaining investment into refining the practice difficult.

The move toward Industry 4.0 could directly help to address that cultural barrier, given that the potential benefits highlighted in the project were enabled by detailed, traceable, retrievable part quality information from inspection. In fact, only through digitalization and increased connectivity will it become possible to realize the true value of NDE inspection data, for instance by enabling immediate, automatic manufacturing process feedback. Moreover, the NDE process itself has the potential to become more sophisticated and capable, for example, through the deployment of AR to give operators real-time feedback during manual inspections, and AI to rapidly and accurately identify defect indications in complex datasets.

For the demonstrator, a web-based database tool was developed, illustrated in Figure 2. The database can accept NDE inspection reports in a number of common formats used industrially. A data miner was written to extract the key

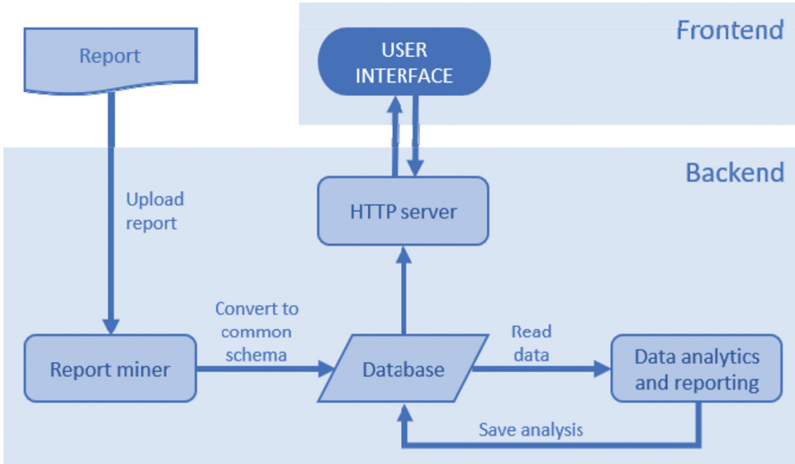

Figure 2. Schematic illustration of the DISMAN tool. NDE inspection reports are converted to a common schema based on the DICONDE standard, then stored as entries in a database, allowing statistical information to be generated by the user.

information from the original files and write this into data schema based on the DICONDE (Digital Imaging and Communication in Non-Destructive Evaluation) standard [8]. This is an NDE image data standard able to accommodate data across a number of different inspection modalities. It also defines a set of Information Object Definitions (IODs) for the storage of specific metadata related to the inspection, and where necessary, new IODs can be defined outside of the standard, as was necessary in this project. After uploading inspection reports, users of the tool are able to validate the extracted data and finally access an analytics page: a customizable dashboard providing statistical information on the inspection data, including historic trends and automatically determined Key Process Indicators (KPIs). This provides an illustration of the value that can be gained through the adoption of even a limited NDE 4.0 framework, without the inspection outputs being saved according to a strict schema.

2.1.2. ENCOMPASS

The recently completed ENCOMPASS project [9] prototyped an Integrated Design Decision Support (IDDS) system software for Laser Powder Bed Fusion (LPBF), a form of Additive Manufacturing (AM) – the quintessential digital manufacturing route. The purpose of the IDDS system is twofold: to provide early feedback on component design from the perspective of manufacturability by reflecting the limitations of build, post-processing and inspection manufacturing stages (enabling design for inspection), and facilitate optimized, targeted post-processing and inspection, informed by events in the build process, as assessed through in-process monitoring on the LPBF machine.

The inspection activities considered X-ray (including Computed Tomography) and visible light (including structured light scanning) modalities. Given that the performance of both is heavily dependent on the orientation of the component, to assess inspectability, a large number of poses were sampled and the inspection coverage assessed for each pose to judge overall inspectability. The assessment of each pose was completed using a lightweight simulation tool developed in-house, considering material path-lengths for X-ray inspection, and optical occlusion (visibility of surface elements and angles of incidence) for visible light inspection techniques. The computed volumetric map of material path lengths was then compared against tabulated X-ray transmission values for the component material and the X-ray source voltage limit of available inspection hardware held in the IDDS database to provide feedback to the designer on the radiographic inspectability of regions of the part. Similarly, the computed occlusion map of the component surface was used to highlight regions inaccessible to post-build processes like laser polishing and machine vision inspection, prompting the designer to take corrective action as appropriate.

Once the design of a component has been finalized, the simulation tools can be reused to suggest an optimized inspection set-up, for instance identifying the best pose for a given imaging-based inspection trajectory. Figure 3 shows an example of this optimization in the context of X-ray Computed Tomography, where the material path length for imaging each volume element of the component (averaged throughout the rotation of the scan) has been significantly reduced by optimizing the pose of the part on the turntable. After the LBPF build has completed, the optimized inspection plan can be further refined by weighting the inspection toward anomalies observed in the build's in-process monitoring data, thereby maximizing the value of the inspection. As the IDDS is an early prototype, the suggested configuration is output in a human-readable report – the next stage would be to extend the output to be a machine-readable file. Note also that the IDDS is able to correlate the

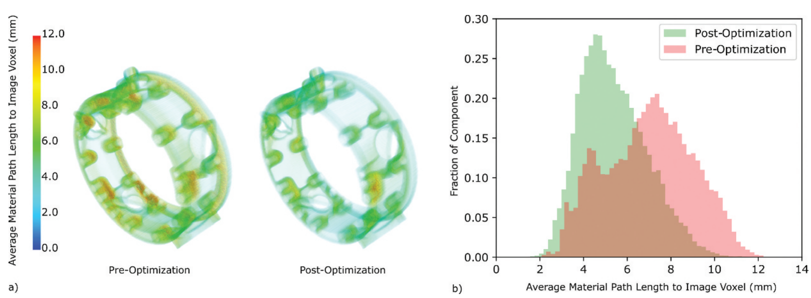

Figure 3. (a) Volume-element (voxel) representation of geometry, mapping the material path length required for each voxel, averaged around an X-ray Computed Tomography scan for initial and post-optimized set-ups, (b) corresponding histogram of values. The achieved reduction in material path lengths is apparent in both. Geometry courtesy of ITP Aero.

downstream actions suggested at the design stage to failures and successes encountered during subsequent manufacture, such that suggested actions can be verified or amended as the IDDS database matures.

2.1.3. DRAMA

As part of the DRAMA (Digital Reconfigurable Additive Manufacturing facilities for Aerospace) project [10], the National Center for Additive Manufacturing at the MTC is setting up a digitalized additive manufacturing facility for use in rapid part and product optimization for AM. The facility's digital infrastructure exploits many core elements of Industry 4.0.

In particular, an environment that enables rapid process development must make full use of modelling, simulation and the vast quantities of data available. Extensive connectivity and efficient data handling are required to expose the data to users and applications. The lack of any all-encompassing data model applicable across the whole AM process chain has led to the implementation of a data lake [11]. The data lake is a repository of data stored in a native state, where, alongside traditional database rows and columns, semi-structured data (for example CSV or JSON files) and unstructured data (such as PDFs and images) can be stored. Data from across the process chain (build files, build logs, powder test data, inspection data, inspection reports, operator production data packs etc.) are captured and input to the data lake through a single interface. No schema or format is imposed on the data upon import; the only requirement is that there is context attached to the data so that it is clear where the data have come from, what part this relates to, how and when this was generated, and who the owner is. This enables easy identification of raw data related to a given component by a simple search against these context data entries. While no strict schema compliance is expected for the raw data, a schema is imposed on the context data, to ensure consistency.

Once data is in the data lake, this can be passed through a data pipeline for additional processing. For example, when inspection data arrive at the data lake interface, by default, the raw data are stored along with the aforementioned context data. However, additional operations can be added to extract component quality insights, and passed to other systems for presentation or further processing, while maintaining the raw, unedited dataset. These data pipelines can be used to add analytics operations and, in the longer term, such operations will determine what data should be retained in the data lake in the first place. Pipelines can also drive more complex tools in an automated manner, enabled by a system architecture which uses open-source software and standard Internet of Things (IoT) protocols including the Advanced Message Queuing Protocol (AMQP) [12].

One such tool relevant to NDE deployed in DRAMA allows for the rapid, initial screening of X-ray Computed Tomography reconstruction volumes/ image stacks obtained for a recently manufactured component. The tool uses a form of AI, a Convolutional Neural Network (CNN), to highlight likely defects to a technician. Importantly, the system is intended to be continuously updated through neural network "retraining". This involves a technician highlighting missed defects and false positives, after which the weights of the neural network can be updated based on the new data. This feedback loop between the algorithm and a skilled operator, with detailed traceability of training data and corrections, lays down a pathway toward qualification of such algorithms for use in a real production environment. However, it should be noted that the deployment of such technologies in a safety-critical context will in practice also necessitate amendments to current regulatory frameworks.

Besides data from post-build inspection, the data lake also hosts the in-process monitoring data from the AM build. A study was completed examining the data from the InfiniAM Spectral system [13], fitted on a Renishaw RenAM 500Q [14] metal LBPF system, which measures both the near infrared and short wavelength infrared emissions from the melt pool region during the build process, as illustrated in Figure 4. The objective was to correlate the signals observed to melt parameters and final part quality. The longer-term intention is to apply AI methods to provide real-time inferences on the quality of the build,

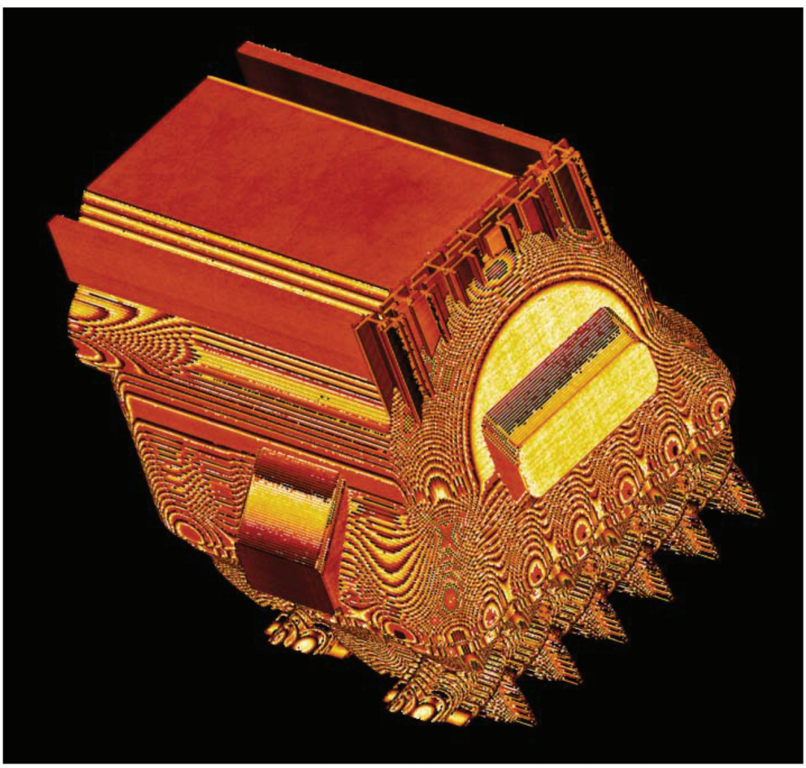

Figure 4. Example of AM in-process monitoring data: volumetric rendering of InfiniAM data, displaying the intensity recorded from the short wavelength infrared melt pool emissions, for a build of a test component.

allowing corrective actions to be taken as soon as possible – in the build itself, or further along the process chain. Efforts on this front are ongoing.

2.1.4. DigiProp

This project [15] involved Dowty Propellers working with three centres of the High Value Manufacturing Catapult, specifically the MTC, NCC and AMRC. A strand led by MTC focussed on the digitization of the collection, management and assessment of NDE data. More specifically, a Jetsoft Overseer [16] database was demonstrated for systematically recording NDE inspection data and meta-data, coupled with a pre-defined defect database to enforce consistency in reporting. Scans were mapped to physical locations on the product CAD, with a demonstration of Jetsoft Tracer [16] for enabling this functionality for manual scans. The improved accessibility and traceability of NDE data enabled improved root cause analysis, as well as the experimental deployment of novel analysis algorithms.

2.2. Past NDE Projects Relevant to NDE 4.0

Past NDE research efforts worth highlighting given close links to the vision of NDE 4.0, without necessarily having been carried out in that context, include work on model-assisted probability of detection (MAPOD) [17], model-assisted inspection qualification [18–20], model-assisted data analysis [21,22], inspection optimization [23], data fusion [24], as well as inspection-based simulation [25–27] and machine leaning, even applied to a traditional, "wet" inspection technique [28]. Work on advanced robotic inspection and un-conventional inspection delivery systems, including collaborative robots (cobots) and unmanned aerial vehicles/drones, are worth highlighting, too, performed especially by the research and technology organization TWI and Strathclyde University [4,29,30]. Moreover, given the role of condition monitoring in NDE 4.0, using embedded sensors to inform a "live" assessment of the state of an asset, much of structural health monitoring (SHM) [31] is broadly relevant and will be further exploited as we move further toward fully digital and connected NDE. Finally, on the interoperability/standardization of NDE data formats, the efforts to establish a common file format for phased array ultrasonic data [32–34], including full matrix capture (FMC), should be highlighted – with the potential to be built upon in NDE 4.0 efforts.

2.3. The Scope for NDE 4.0 Learning from Related Fields

A great deal of work relevant to NDE 4.0 has already been done in the world of dimensional metrology. In particular, the field has made great progress in the use of the digital thread, the chain of digital data captured and analyzed across the process chain, from design to manufacturing and inspection, using the implementation of model-based definition (MBD) and data interoperability standards such as the Quality Information Framework (QIF) [35]. MBD is a digital 3D model used as the authority design specification of the part. It is the single source of design truth, containing the information to drive all downstream manufacturing and inspection activities throughout the rest of the process chain.

An organization that runs all its processes from the authority MBD model is called a model-based enterprise (MBE). Much of the research efforts for MBEs worldwide have focused on quality departments, as it is perceived as being one of the "low hanging fruit" for capitalizing on MBD. Dimensions and tolerances are a major part of existing product definition data, traditionally present in 2D engineering drawings. Within dimensional metrology, the data have well-defined standards, making it relatively easy to digitize and link to CAD model surfaces. This being stored within an MBD instance means that downstream inspection planning and programming software can pull through the CAD geometry, feature nominal characteristics and tolerance values. This automatically forms the base of an inspection program without the need for manual interpretation or data entry, reducing errors and duplicated effort.

Once a program is produced and an inspection takes place, the evaluated measurement results can also be stored digitally with the features and characteristics in the MBD, forming a key part of the product Digital Twin. This gives an increased level of data traceability and provides context to inspection results as engineers can quickly visualize issues and better understand their criticality. Directly linking dimensional measurement results in design characteristics also unlocks further, more advanced analytics possibilities. Through a series of projects, incorporating product lifecycle management (PLM) systems and mapping manufacturing data to MBD characteristics, the MTC has demonstrated some potential benefits of digital manufacturing [36–39]:

- Intelligent process control, where manufacturing processes are optimized to maximize the quality of subsequent parts through improved understanding of the factors influencing final part quality.
- Root cause analysis, where the digital thread enables the investigation into the reasons for poor part quality or poor machining performance.
- Adaptive inspection planning, where inspection plans are dynamic enough to allow removal of trusted features with good process capability, reducing load from overburdened measurement equipment.

The MTC also collaborated with other centers of the High Value Manufacturing Catapult [6], specifically the National Composites Center (NCC), Advanced Manufacturing Research Center (AMRC) and Nuclear Advanced Manufacturing Research Center (NAMRC), in the project "Metrology for Industry 4.0". This examined barriers to the adoption of Industry 4.0 practices, both through a workshop with industry partners, and a study on the interoperability of MBD in several different design environments, based on the digitization of drawings for two test geometries. Although significant variations in the level of support of different CAD packages were observed, two workflows were successfully demonstrated simulating typical supply chain relationships. The MBD was designed in one centre (acting as OEM), including design review and qualification, before being passed to another centre (acting as supplier) for programming and inspection – finally the results were passed back to the original centre (OEM) for review.

2.4. Projects on Industry 4.0 with Notable NDE 4.0 Applications

Moving still further away from the NDE domain, there have been numerous Industry 4.0 projects relevant to NDE 4.0 that the NDE community should expect to be able to build on. Of course, there are generic Industry 4.0 activities, for instance relating to secure communication protocols between IoT/connected devices, that will be of use in an NDE 4.0 context, but these are too generic to be spelt out here. More specifically appropriate to the field are activities on AR, for example: the authors are aware of a project to bring Augmented Reality (AR) to assembly/maintenance/inspection tasks, using Microsoft Hololens headsets [40] to display interactive operator instructions – see illustration in Figure 5 [41]. Additionally, the demonstrated use of AI to

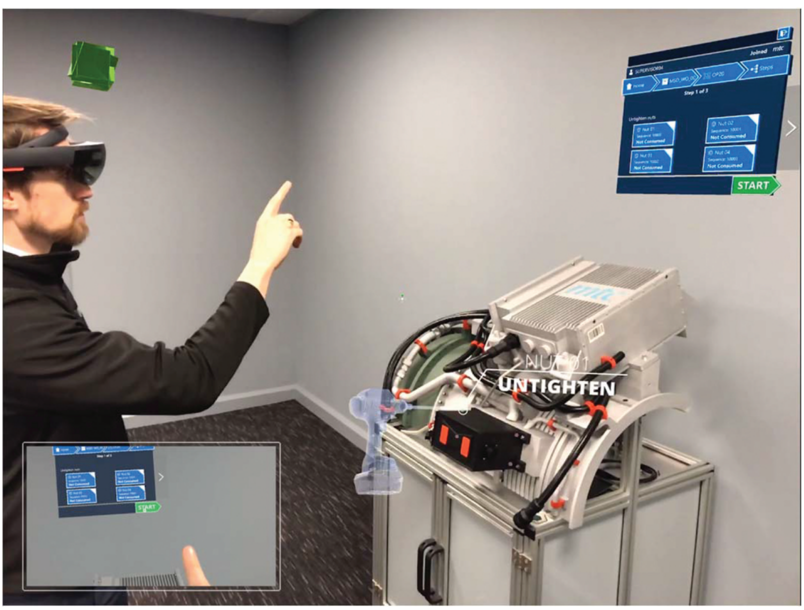

Figure 5. Screen capture from a cooperative demonstration of AR for a maintenance task. The "supervisor's" view is shown. This consists of the current scene with current instruction overlays and process menu generated for the "operator". A section of the "operator's view" is also provided as an inset, related to the selected "operator" as marked by the floating geometric icon.

monitor a video feed and then trigger warnings (or e.g. lock the operation of equipment) if a person is detected without appropriate Personal Protective Equipment (PPE), clearly has applications in NDE for ensuring the improved safety of operators [42].

3. Current Activities & Future Plans

A project launched very recently contributing directly to the advancement of NDE 4.0 is "Digital Inspection Requirements Enhancing Coverage and Traceability (DIRECT)". This MTC membership project, backed by a steering group of 20 companies, seeks to expand on previous efforts on MBD, specifically to digitalize part specifications relevant to NDE (and surface metrology/topology), incorporating them into MBD data, so as to bring these inspection domains in line with Industry 4.0 methodologies. The intention is then to demonstrate two applications of this approach: the streamlined co-location and visualization of dissimilar datasets in the same coordinate system, to enable data fusion, and the automation of an inspection through the automatic generation of a machine-readable inspection design through simulation from the part's MBD.

A Center for Digital Engineering Technology and Innovation (DETI) was announced recently in the West of England. DETI is a research, innovation and skills initiative – a collaboration of industry and academic partners led by the NCC – which sets out to develop and accelerate digital engineering across multiple industry sectors – to benefit future generations of engineers and engineering products, and to help tackle global challenges [43].

Beyond that, there are of course many planned activities, across a range of research groups and sectors, to unlock further the potential of NDE 4.0. Amongst the activities on the MTC NDE roadmaps in this space are forms of adaptive inspection, supported by advanced/novel qualification approaches, and engagement with the NDE supply chain to, for example, support inspection service providers to handle fully digital inspection requirements. The corresponding elements of the Metrology roadmap are based on driving the adoption of model-based processes within management systems (such as PLM and MES – Manufacturing Execution System), to unlock value by essentially making the inspection results an integral part of the manufacturing system, not an afterthought at the end of the process chain.

3.1. The Strategic View – Technologies

At a higher, more strategic, level the RCNDE has identified six NDE technology challenges that will become barriers to reaching the ANDIV vision of NDE 4.0 if not addressed by the NDE community:

(1) New NDE methods for new manufacturing: in AM, a shortfall in NDE capability, both at manufacture and in-service, has been identified as the primary barrier to structural use of AM components [20]. In intelligent process control, NDE information is required as an input, requiring new in-line inspection techniques that can be integrated into the build process [44]. To realize one of the key benefits of AM components, automatic procedures for designing and qualifying in-service inspections for complex-shaped parts need to be developed, ideally as part of the component's design process.
(2) Robotics and automation: automated deployment of NDE is already performed in manufacturing environments and for in-service inspections of certain common geometries (e.g. pipe girth welds [45]). However, in NDE 4.0 the expectation is that robots or cobots increasingly replace all manual inspection. This requires new forms of automation and new NDE sensors and inspection philosophies that are optimized for field deployment by robots in less controlled environments.
(3) Sensors: the Industry 4.0 vision of an asset Digital Twin requires permanently installed sensors that provide data to facilitate live decisions on integrity. Many of the required sensors are not available, especially for harsh environments, and updated measurement philosophies are needed to integrate NDE information from sparse, distributed-sensor systems. The qualification of such sensor systems also requires fundamentally different approaches to those for conventional NDE techniques.
(4) Analytics: new methods are needed for processing data on operational-loads and structural condition from a wide range of sensors to continually improve life prediction based on data mining and statistical combination of information from diverse sources. Key challenges are dealing with complex datasets from multiple sources that describe different physical quantities (e.g. temperature, ultrasonic contrast, X-ray absorption) and are highly heterogeneous (e.g. with different dimensionality, temporal resolution, spatial resolution and positional uncertainty).
(5) Artificial Intelligence: some form of AI, most likely machine learning, is likely to provide the only viable route for dealing with the volume and complexity of data associated with NDE 4.0. However, automated analysis using AI breaks the link between measurements and physics-based interpretation, hence new methods of inspection qualification are needed.
(6) Modelling and simulation: both training and qualification of AI for NDE require provision of training data in much higher volumes than before. Such volumes can only be generated through simulation, but to

be useful, the simulated data must be indistinguishable from real data. New, scalable high-fidelity modelling methods are needed to achieve this. Structural-integrity modelling is also required for performance- and life-prediction.

These challenges are illustrated across the product lifecycle in Figure 6.

3.2. The Strategic View – Skills

Meanwhile, the British Institute of Nondestructive Testing (BINDT) has initiated a program to identify and address the operational and skills challenges of the part of industry that successfully embraces the benefits of NDE 4.0. This includes examining the role of the human in the new human-machine interactions [46].

It is thought that NDE personnel will still be required in similar numbers to the present day, but their roles and skillsets will be different and will be applied at earlier stages in the product lifecycle. More emphasis will be placed on design-stage development of automated data acquisition and analysis processes and their validation, while there will be a reduced requirement for skilled NDE practitioners working on in-service assets because of the increasing role of autonomous verification systems, including embedded sensors [47]. However, the autonomous systems will still be supervised by skilled and experienced humans, who will also actively shape and modify the systems.

In cases where decisions are not completely taken away from humans – known as an "automation gap" – there will be a higher level of "technical assistance" provided, such that the large amount of available data is processed

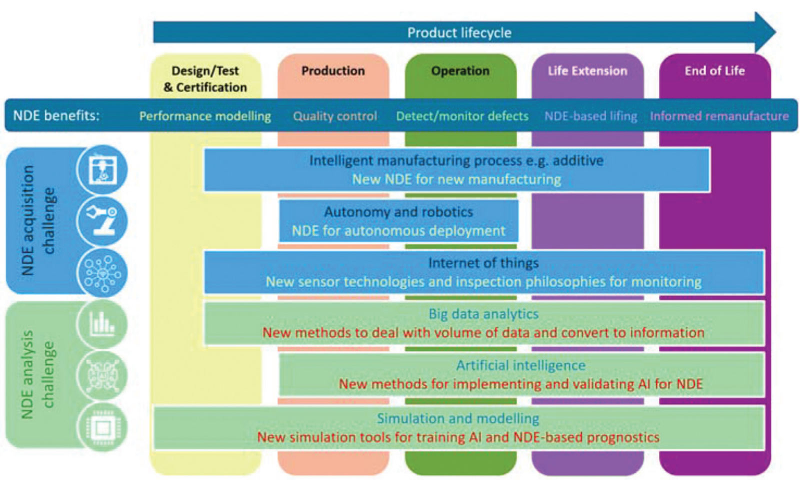

Figure 6. Illustration of the RCNDE's six key technology challenges, three in data acquisition and three in analysis, across the product lifecycle.

and analyzed, converting it to information and putting the decision within the cognitive capability of the human. One might recognize that this is a scaled-up version of what many digital flaw detection systems already do.

In response to this future challenge, BINDT is establishing an NDE Leadership Forum which will look strategically across the industry to advise government and initiate action in areas that are currently not being addressed. It is wider in scope than NDE 4.0 and it is expected that much of the activity will be inspired by the needs of Industry 4.0.

The Leadership Forum will have five pillars of activity:

(1) Landscaping: this will be primarily about advising UK government on the state of the NDE industry and the future challenges and requirements. This includes liaison with regulators, to help ensure that 20th Century legal and contractual requirements do not unduly impede the uptake of 21st Century technologies.
(2) Engineering: as well as reaching out to designers to promote "design for inspection" and implementation of NDE 4.0 principles, this pillar also covers the development of an "NDE Engineer" career route covering the skills required for technology and technique validation including automated systems.
(3) Requirements: this pillar will capture and publish the NDE requirements for specific sectors and even for particular materials or structures within a sector, as well as establishing special interest groups to tackle the meeting of these requirements.
(4) Research: beyond the strategic activities of the RCNDE, an NDE Research Network will be established, which will probably be international.
(5) Technology: this pillar covers all the aspects of transitioning technologies into industry including technique qualification, model-assisted qualification, and standardization of methods and data formats. It will link with technology user groups within BINDT and ICNDT (International Committee for Non-Destructive Testing) and with the applied research Catapult [6] centres (such as the MTC) in the UK.

4. Discussion

Clearly, a major challenge for the full adoption of NDE 4.0, and exploitation of the associated benefits, is the ability to re-use data in multiple places along the manufacturing process chain and through the entire product lifecycle. Given that NDE data will be an input to numerous downstream processes in the process chain/product lifecycle, an understanding needs to be developed of the needs of those NDE data users (likely outside domain) to unlock the full set of potential business benefits. In an MBE implementation, the design model and associated data must be consumed and understood by management, manufacturing and inspection software, adding to the data as appropriate. Since this can involve multiple software vendors, based in different domains, there are often format incompatibilities. The development and uptake of open standards and common file formats is therefore important to have a robust, long-term means of transferring data through organizations and supply chains.

STEP AP.242 is an ISO standard for MBD product definition [48] that is becoming more widely used in software. The Quality Information Framework (QIF) [35,49] then takes the concept further by supporting all dimensional quality information, from the MBD itself, to resources, measurement plans, results and part-to-part statistics. The benefits of this is that each process step can consume the upstream data, add to it in the same format, and pass it all downstream for use in the next process. Further development and increased adoption of open standards within industrial software is critical for widespread realization of the benefits of NDE 4.0, and more generally MBE.

This push for open data standards and interoperability should be recognized to have significant likely impacts on working and commercial practices in the NDE world. For example, end-users will be more able to “mix and match” equipment depending on technical and commercial preferences, while the closed, proprietary “ecosystems” that some suppliers have built up will be side-stepped, with a likelihood of these being opened up or discontinued in the long-term.

A comprehensive implementation of NDE 4.0 will require the regulations governing safety-critical industries to be updated to allow decisions to be made, or at least supported/recommended, by novel algorithms. The question of liability in the event of a catastrophic failure in such a context will also need to be addressed. Tools to support qualification/certification will be needed, for example considering the quality of software used. However, there is much that can be done toward NDE 4.0 without being limited by regulations, for example by recording inspections in a manner that allows downstream processes to extract additional value.

The rise of NDE 4.0 will also give rise to changes for NDE practitioners. In the shorter term there will be fewer wet sign-offs of paperwork, in the longer term the growing role of algorithms and automation will mean that the development/testing/validation of digital systems becomes the focus of careers in the field, with implications for the skill sets required and qualifications to be made available.

5. Conclusions

This paper has described a vision of NDE 4.0, some of the progress toward it, and the challenges industry faces in moving to this new paradigm. The NDE community is embarking on a journey to adopt and contribute to Industry 4.0 practices – and as with almost any major change, there are associated challenges and opportunities, for companies and individuals. Amongst the opportunities is the potential for NDE to become more capable and valuable/valued, given the extended impact enabled through more widespread use of the generated data. Challenges include interoperability, not only between products from different equipment suppliers but also between domains and through the product life-cycle, and hence the need for standardization of data formats.

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