Enabling the Fourth Industrial Revolution (4IR) and the role of NDE and monitoring

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The Fourth Industrial Revolution (4IR) is happening all around us, whether it is the emergence of self-driving vehicles, autonomous 'healthcare' robots or the transformation of industrial activities and infrastructure. Non-destructive evaluation (NDE) and permanent structural monitoring will both be impacted by 4IR and will also be enablers for the transition to 4IR. The UK Research Centre in NDE (RCNDE) is established as a leading academic-industrial collaboration for undertaking industrially-relevant research in the fields of NDE and structural health monitoring. The industrial members of RCNDE produced their first 5-, 10- and 20-year vision for NDE in 2011. This article describes the industrial members' newly-updated vision for NDE, which still includes many of the original priorities relating to future NDE requirements for existing assets and infrastructure. However, this updated industrial vision for NDE also identifies how NDE and monitoring technologies will need to adapt for 4IR and the contributions they will make towards realising this future industrial paradigm.

As reported previously, the UK Research Centre in NDE (RCNDE) is an industry-academic collaboration for NDE research founded in 2003 and co-funded by the Engineering and Physical Sciences Research Council (EPSRC) and its industrial membership. The industrial membership has grown from five members at the outset to around 50 today. These include thirteen full end-user members, covering the aerospace, power generation, nuclear, oil & gas, defence and manufacturing sectors. In addition, there are now around 37 NDE supply chain associate members covering all sizes of company, from the smallest SME to large NDE divisions of transnational businesses. A not-for-profit company, NDE Research Association Ltd (NDEvR), which manages the affairs of RCNDE, collectively represents the industrial members of RCNDE. In 2014, NDEvR renewed its strategic partnership with EPSRC, which will now run until at least 2020, with the purpose of furthering longer-term NDE research and refreshing and building the UK NDE research and industrial skills base. The continued support for RCNDE, both industrial and from EPSRC, together with the associated Industrial Doctoral Training Centre, reflects the importance of inspection and monitoring technologies in providing essential enabling capabilities to meet company and national goals for industrial productivity and economic growth.

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From the outset, the industrial member companies of RCNDE recognised that future advances in NDE technologies had to be planned and funded, from the early-stage basic research programmes through to the pre-competitive stages of technology transfer. Otherwise, the NDE capabilities necessary to underpin their businesses would not be available on the right timescales. This would undermine their ability to innovate with new designs and materials and to maintain and improve their international competitiveness. Therefore, an important task for RCNDE members is preparing and maintaining a collective view of the future requirements for NDE in their respective industry sectors and, more specifically, at 5-, 10- and 20-year horizons. This article updates the previous article published in *Insight* in 2012[1].

In 2011, the industrial members produced their first 5-, 10- and 20-year vision for NDE, which was extensively used to inform the direction of RCNDE and other university research. The vision also proved to be a key conduit to government and public bodies, demonstrating a strong cross-sector synergy and delivering a coherent message for the importance of NDE and the ongoing requirement to pursue challenging research goals that will benefit both multiple and strategically-important industrial sectors. In short, the '5-10-20 vision' brought further credibility and the combined weight of industry to help justify and provide evidence for ongoing government support for research, technology transfer and training.

The industrial members of RCNDE sought to update the original vision throughout 2016 and to look at the next 5-, 10- and 20-year requirements for NDE. Once again, preparation of the vision considered individual industry sector trends, technological possibilities, emerging innovations and future sector and company needs. This was undertaken in the context of a broad range of drivers, including market, regulatory, safety, environmental and economic factors. Naturally, it also involved reviewing the 2011 vision and identifying the progression of capabilities and changes in industrial priorities. In some cases, the requirements of five years ago have disappeared, such as the NDE relating to future high-temperature 'clean' fossil power generation. In other areas, there has been clear progress in moving NDE technologies and capabilities up the technology readiness level (TRL) scale[2]. The 5-10-20 vision has helped bring focus to both research into future NDE and bringing advances in NDE into industrial use.

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[1] 'RCNDE Industrial members' vision for the future requirements for NDE', Insight, Vol 54, No 3, pp 124-127, March 2012.

[2] Technology readiness levels are a standard means of assessing the stage of development and innovation of novel ideas and techniques. TRL1 represents the most basic understanding of new principles and ideas, while TRL9 represents the routine use of an idea or technique in industry. TRL1-3 is typically the realm of university research and TRL7-9 is the commercialisation of new products and processes. TRL 4-6 is recognised as the main gap to bridge and necessary for successful innovation.

The new NDEvR 5-10-20 vision[3] is anticipating the requirements for inspection technologies for a society embarking on the Fourth Industrial Revolution (4IR). The first industrial revolution began in Britain in the late 18th century with the mechanisation of the textile industry. Tasks previously carried out laboriously by hand, as 'cottage industries', were brought together to form factories. The second industrial revolution came in the early 20th century, with the mastery of the moving assembly line and the age of mass production. The third industrial revolution in the latter half of the 20th century, sometimes referred to as the 'digital revolution', saw the advent of microprocessors and high levels of automation. The 4IR (variously referred to around the world as Industrie 4.0, Industrie du Futur, Produktion 2030, etc) reflects the coming together of digital and physical networks to create opportunities for the fusion of multiple technologies and new autonomous systems. It is characterised by recent and anticipated breakthroughs in fields such as artificial intelligence (AI), automated robotics and advanced manufacturing, pervasive digital networking (the 'Internet of Things'), autonomous vehicles, processes, plant and infrastructure, 3D printing and additive manufacturing, 'Big Data' analytics, materials science and nanotechnology, among other things. Future manufacturing and infrastructure will involve self-optimisation, self-configuration, self-diagnosis and resource efficiency. Inspection and monitoring technologies will have a key role in the transition to the 4IR.

Most companies have clear ideas of their future requirements for NDE to enable fulfilment of their business plans. Each of the industry sectors represented by NDEvR considered their near-, medium- and long-term horizons mapped to 5, 10 and 20 years into the future. While several hundred individual targets were identified, Table 1 provides a summary of the trends common

[3]With contributions from Airbus, Amec Foster Wheeler, BAE Systems, BP, DSTL, EDF Energy (and EDF R&D in France), Hitachi, National Nuclear Laboratory (on behalf of and funded by the Nuclear Decommissioning Agency for the benefit of its estate, including input from the site operator Sellafield Ltd), Rolls-Royce, RWE npower, Shell, SKF, Tenaris and Uniper.

Table 1. Summary of NDEvR members' 5-, 10- and 20-year vision for NDE (2016)

5 years	10 years	20 years
Future inspection technologies		
• Replacing/updating current inspection technologies • Measuring and using material knowledge to improve detection and characterisation • Coping with complex geometries, including through layers and past obstructions • Reducing/eliminating manual inspection with wider use of robots and manipulators, permanently-installed and embedded sensors and localised structural health monitoring (SHM) • Improving 'real-world' models and experimental validation; real-time data fusion and robust automated data interpretation	• Screening, monitoring and 'connected' sensor networks • Targeted NDE with remote and automated NDE • Automated adaptation for material properties to provide higher sensitivity • Measuring material mechanical properties • Suite of modelling tools and experimental validation • Universal remote autonomous NDE deployment tools • Real-time automated data processing and assisted decision making • Common data format and file size reduction • Physical model-based determination of probability of detection (POD).	• Material-independent, high-sensitivity inspection with full volumetric mapping • Biological sensors • Rapid, long-range and wide-area non-contact inspection • Interoperability of NDE and monitoring systems and fully-automated data analysis • Artificial intelligence in systems • Full integration of inspection modelling with materials and integrity engineering • 'Digital twin' capability for cradle-to-grave integrity evaluation, including assessment of performance reduction based on defect monitoring
Future infrastructure inspection		
• Minimised manual inspection • Widely used robots and manipulators for field/industrial inspection and for difficult access/harsh environments • Long-life, reliable permanent sensors and networks with sensitivity to monitor defect changes, and localised SHM in key inaccessible areas	• Wider use of monitoring for large-area screening and larger area SHM • Extended life automatic self-calibrating sensors • NDE targeted by monitoring • Wide range of universal platforms for remote and automated NDE (crawlers, UAV, etc) for ultrafast inspection	• Fully-instrumented plant and systems on scales of 10-100 km • Field-ready methods for self-monitoring and smart structures • Integration of monitoring/NDE and plant parameters for fully-informed integrity assurance and plant optimisation
Future manufacturing inspection		
• Trend to in-process monitoring for manufacturing processes (metals and non-metals) • Inspection of 3D-printed components • High-accuracy robotic NDE for large complex-shaped components	• Online inspection of 3D-printed components • Fast, online tomographic inspection • In-process inspection matching post-manufacturing inspection performance	• 'Inspection-assured' tailored materials • 'Design for inspection' implemented • Holistic estimation of product/component quality referenced to predicted in-service performance • Processes fully monitored from raw material to customer • Inspection processes not impacting on cycle times/rate

to most industrial sectors for the progression towards and through the 4IR. This summary comprises three principal parts: the vision for future inspection technologies, future infrastructure inspection and future manufacturing inspection. However, within these categories, the full 5-10-20 vision considers the requirements for coping with the challenges involving materials (for example coarse-grained metals, composites, coatings and surface treatments, printed materials, etc), defect characterisation and inspection sensitivity, complex shapes and geometries, next-generation manufacturing and access constraints and operating environments. In addition, two other key themes relate to inspection automation and inspection modelling and data. Inspection automation includes robotics, permanent monitoring, sensor technologies, data collection, automated and assisted analytics and decision-making and addressing human factors. Inspection modelling and data management are necessary to facilitate probably all of the advances envisaged through real-world models, simulation and validation, data fusion, handling and management (for example data file size reduction), as well as better approaches to reliability and for judging and predicting integrity.

For setting the five-year vision, the approach considered what had been state of the art five years before, what had changed since and what may represent the future application of known emerging technologies and solutions. By matching the requirements of each company's near-term business planning with knowledge of current pioneering technologies (for example those currently at TRL3 were deemed to be good candidates), the five-year vision seeks to establish what the business needs for NDE will be over this period. The detailed vision is expressed as much as possible in terms of specific and quantifiable goals, such as factor improvements in performance (for example speed, coverage, range, etc). The next five years will see the inexorable upgrading and replacing of current NDE with better NDE performance. This will be achieved with increased automation of data collection, processing and interpretation, together with the application of emerging material measurement capabilities supported by more powerful and realistic modelling. This will include coping with lossy or noisy materials for improved range and sensitivity and reliably detecting and characterising smaller defects and defects in difficult-to-access regions (for example near-surface and close-to-back-wall locations). The roll-out of infrastructure monitoring will continue, including higher fidelity structural health monitoring of localised high-impact regions of plant and structures. Over these five years, manufacturing NDE will help to enable the evolution of manufacturing technology advances envisioned for the 4IR, such as the wider use of additive manufacturing and the adoption of advanced materials and component designs. These advances will bring manufacturing industries closer to the goal of in-process monitoring with high-precision, high-speed robotic NDE and high-temperature and non-contact inspection.

The 10-year vision draws heavily on 'next generation' technologies. Defining business needs in NDE terms requires an understanding of where the individual businesses expect to be in 10 years' time and involves consultation with colleagues within members' organisations regarding the use of NDE data and any perceived limitations. The scoping of technologies potentially able to meet these future needs is somewhat more speculative, although there is usually already the kernel of knowledge and understanding to justify candidate technologies. Indeed, for 10 years' time, the vision generally relates to current or planned research activities, including those presently at TRL1-2. Therefore, the necessary development paths are broadly apparent today, albeit with some imagination and, once again, goal setting is specific where possible as well as including some conceptual goals. Inspection technologies in 10 years' time are expected to depend significantly on wide-area, connected permanent and embedded sensor networks for screening structures to detect emerging degradation, including high-sensitivity measurement of defect growth rates. These will require extended-life auto-calibrating sensors. *In-situ* NDE targeted at critical regions will be delivered by remote operation using universal automated NDE platforms. Increasing automation will include measuring, and then adapting to, material properties for improved defect detection and characterisation sensitivity, automatic data processing and model-assisted decision support. Human factors affecting inspection quality and data sentencing and interpretation will be greatly reduced. Improvements in the inspection of materials will include progress with the sizing of very small defects (*ie* few tens of microns) in thick sections and the assessment of mechanical properties and material condition (such as hardness, residual stress and stress depth profiling). Important steps towards the digital ubiquity for the 4IR will include advances in data handling and common data formats. The manufacturing industries will employ in-process inspection matching the performance of post-manufacturing inspection, and online inspection of 3D-printed components will have been implemented with validated acceptance criteria.

Looking to 20 years ahead, the industrial vision for NDE is much more speculative. It is important that new ideas are explored without hindrance from current knowledge of capability. Therefore, the industrial sectors were asked to consider the 'can't do' areas of NDE, including tasks where NDE is not currently used or envisaged, for example where the prevailing alternative is to scrap, strip or replace. The 20-year visions assume advances in all supportive technologies, such as computer processing speeds, data storage capacity, etc. They also envisage that the required understanding will exist for all facets of the engineering problems for which an NDE detection or measurement capability might be relevant. Nevertheless, the NDE and monitoring community will still need to reach out to other engineering disciplines to identify opportunities for new engineering practice, for example through closer understanding between the fields of NDE and structural integrity. These opportunities will arise from advances in inspection technologies and capabilities to enable better engineering integrity judgements and decisions and the potential for new or improved approaches to engineering integrity. This is a distant horizon and, once again, some goals are specific and others conceptual. The prospects for 20 years from now include high-sensitivity full volumetric inspection independent of material, with fully-automated analysis decision-making and built-in artificial intelligence integrated with comprehensive material and integrity engineering models: the 'digital twin' replica of physical assets and how they are performing. Inspection capabilities will include ultrafast, long-range and wide-area sensing with extensive distributed systems spanning tens to hundreds of kilometres, with built-in self-monitoring and condition diagnosis. Defect characterisation will extend to fatigue and other damage precursors as well as characterisation of material changes and condition in wider areas and bond integrity. These capabilities will be possible in challenging plant conditions and hazardous environments (for example raised temperature, ageing plant, deep water and high radiation environments). Where applicable, structural monitoring approaches will be based on defect growth rates (rather than absolute defect size), which should provide improved sensitivity and better predictions of future structural integrity. Manufacturing in the late 2030s will deploy inspection for assuring the performance of tailored materials, with product quality referenced to predicted in-service duty performance. Inspection processes will not affect manufacturing cycle times.

Summary

In my 2012 article, I asked 'what comes next?' and I described it as 'beyond NDE', with trends towards:

- greatly reducing the use of disruptive in-service NDE and eliminating it in certain key applications;
- far greater application of real-time automated inspection aimed at achieving defect-free manufacturing;
- the extensive use of online structural health monitoring and smart structures, albeit supported by precision-targeted high-performance NDE; and
- the comprehensive use of data from all engineering disciplines for structural integrity decisions based on actual operational conditions and duty cycles.

Whilst much of this prediction remains valid, a new aspect that was not previously highlighted by the original 5-10-20 vision is the importance of networks and connectedness of sensors, systems, infrastructure and engineering disciplines, together with the opportunities these provide for autonomy based on realistic models, robotics and machine learning and moves towards artificial intelligence.

The 'foresighting' process and the updated vision will once again be used in a variety of ways. The industry-sector visions provide strategic input to help companies define their research and innovation programmes. Some themes of wider cross-sector or cross-discipline interest, which are either very new or the opportunities are yet to be explored, will be adopted as key areas of research for collaboration between industry, EPSRC and the universities, and through the NDEvR-EPSRC strategic partnership. These topics will shape the RCNDE core research programmes into the future and open up opportunities for new collaborations, both within and outside the current RCNDE membership, as elective research projects, for example via the RCNDE targeted research programme or via other UK university research initiatives. In addition to the research vision, NDEvR members will identify, initiate and collaborate on activities that bring forward the application of inspection and monitoring technologies to meet these future industrial needs and timescales.

The Fourth Industrial Revolution, however it is described, is happening in all aspects of society. Inspection technologies will become integral to future smart infrastructure and systems through the networks of sensors that they must inevitably contain. The convergence of operational, environmental, inspection and monitoring data will demand the integration of previously discrete disciplines, approaches and systems.