The NDE 4.0: 
Key Challenges, Use Cases, and Adaption

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Abstract

Historians split recent times into three industrial revolutions: mechanization (steam power), technical (electric power and mass production), and digital (computing and microelectronics). The world of NDE has a parallel: tools to sharpen human senses, wave application to view inside the components, and digital processing and automation.

As the industry goes through the fourth revolution powered by interconnections and enhanced digitalization, NDE is also on a new horizon: NDE 4.0 with information transparency, technical assistance, autonomous, and decentralized decisions. Technologies such as IIoT, AR, AI, 5G, and blockchains are opening up new inspection and safety assurance possibilities in every industrial sector.

To establish a proper foundation for technical research on this emerging subject, it is important to first research the perception of stakeholders, misconceptions around NDE, the value proposition of NDE 4.0, the challenges and opportunities, and even outline a process to pursue it. This paper presents a critical view of current thinking and major use cases for NDE 4.0 – both Industry 4.0 for NDE and NDE 4.0 for Industry; all leading up to a safer, cheaper, faster, and reliable inspection eco-system. It also dwells upon challenges such as skills relevance, adoption, and leadership in the cyber-physical world.

Keywords: NDE 4.0, Use Cases, Advanced NDE, Future of NDE, Automation, NDT 4.0, Industry 4.0, Industrie 4.0, NDE Challenges, Digital Twin, IIoT, OPC UA, Ontology, Semantic Interoperability, Industrial Revolution, ISO 56002, SHM

Notes

This paper presents the early stages on the road to NDE 4.0. It presents a survey-based research on the questions “What is NDE 4.0” to identify its major use cases. Meaning, research about opportunities, challenges, approach, … . Therefore, it can also be seen as an orientation to NDE 4.0 with a specific purpose to bring awareness and familiarity with the subject.

Introduction to Industry 4.0

The term Industrie 4.0 (German for Industry 4.0) was introduced in 2011 at the Hannovermesse in Germany [1] to give a name to all the ongoing activities which will eventually lead to the fourth industrial revolution [2,3].

Like the other industrial revolutions (ref to Figure 1), the fourth revolution is shaped by new markets / industries and in particular by new emerging technologies, like digital twin, industrial internet of things, cloud, 5G, augmented reality, artificial intelligence, big data, additive manufacturing, digitalization, robotics and drones,
blockchains, and quantum computers. Looking at the emerging technologies connected with Industry 4.0 it gets clear that this fourth revolution is data driven.

![Figure 1](image)

**Figure 1** Visualization of the four industrial and NDE revolutions based on [2,3]
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**Industry 4.0 Emerging Technologies**

Before addressing the question of NDE 4.0 the following presents an overview of the Industry 4.0 emerging technologies. This enables a later discussion whether those technologies give more value to NDE data, and whether they create new use cases.

**Digital Twin**

The digital twin encapsulates all data of an asset / of a component and allows to simulate the asset based on the stored data. A digital twin of a human, for example, would encapsulate all data in connection with the human, like dimensions (weight, length, ...), financial aspects, connections (friends, colleagues), eating and drinking preferences, health history, .... Therefore, social media cites (like Facebook or LinkedIn), user accounts (like Google or Apple), health insurance records or governmental records can be considered partial digital twins. With simulation tools added the behavior or the lifetime of a human can be predicted by those digital twins. This already shows on the one side the importance of data security and data sovereignty but on the other side the value of data.

One of the first implementations by an independent body for a digital twin is the asset administration shell of the platform Industry 4.0 [2,3].

**IoT: Industrial Internet of Things**

The industrial internet of things (IoT) is going to connect all assets with each other, with the digital twin, with data-base systems, and with the cloud. For this it uses standard / core communication interfaces like OPC UA, DDS, WebServices, or oneM2M and core gateways to connect the core communication standards with each other. The development of each of the standard communication interfaces is driven by an organization (like the OPC UA Foundation for OPC UA). The Industrial Internet Consortium (IIC) requires the core gateways and the International Data Spaces Association (IDSA) is in the process of implementing the IDS connectors to connect all the communication standards with digital twins, the cloud, and data markets while guaranteeing the data sovereignty [2].

**Semantic Interoperability, Ontologies**

Dealing with communication standards, digital twins, or data types/formats one key aspect is to give data unambiguous, shared meaning, which is achieved by semantic interoperability, by ontologies. Syntactic interoperability is the necessary basis for semantic interoperability converting the data from a system-dependent to a system-independent format and thus enables data exchange between different systems. However, for a computer to understand data (just like for a human) the computer needs to know the unit of the submitted
number, it needs to know whether the number refers to a height, a length, a weight, a time, … , and it needs to know the connections between the objects. For example, that a car has a speedometer and the speedometer shows a value of 136 km/h. This is enabled by semantic interoperability by not only storing a value but also by identifying its connections and therefore giving it meaning.

Cloud

Another technology connected to Industry 4.0 is cloud computing. Cloud computing enables the access to an IT infrastructure using the internet from any computing device around the globe and allows data storage, data processing and application software as a service. For a reasonable use of clouds semantic interoperability of data and of the communication interfaces are key so that the standard data processing and visualization software available in the cloud can understand the data.

5G

5G is on the one hand the successor of 4G for faster mobile data exchange – that part of 5G is called eMBB (Enhanced Mobile Broadband). However, 5G has two additional modes which makes 5G one of the corner stones of Industry 4.0:

- Ultra Reliable Low Latency Communications (URLLC) allows robust real time data connections (latencies with at maximum 1 ms) and extended mobility (500+ km/h).
- Massive Machine Type Communications (mMTC) allows the connection of high numbers of devices (1 million/km²) and cheap low complex mobile implementations.

Therefore, 5G spans all the way from very fast to real time to high device density.

AR: Augmented Reality

Virtual reality (VR) utilizes headsets to display a computer-generated virtual reality (for example generated by a computer game). It therefore blocks the normal human reality. Augmented reality (AR) presents an interactive experience of a real-world environment where objects in the real world are enhanced by computer-generated visualizations of data by mobile devices or AR headsets / smart glasses. Therefore, it mixes / augments normal human reality with a computer-generated virtual reality. Augmented virtuality (AV) uses VR headsets but the virtual reality (virtuality) is enhanced with real world information (audio, visual, …). Therefore, it first blocks the normal human reality like VR, but it later mixes / augments the computer-generated virtual reality with information from the normal human reality. In mixed reality (MR) VR, AR, AV and normal reality are mixed. Finally, the term XR is used to summarize all four VR, AR, AV, and MR.

AI: Artificial Intelligence

Artificial intelligence (AI) is defined as “A system’s ability to correctly interpret external data, to learn from such data, and to use those learnings to achieve specific goals and tasks through flexible adaptation” [4]. It is not synonymous to machine learning, deep learning or neural networks. In fact, as Figure 2 shows, artificial algorithms are a subset of algorithms which have the ability to mimic human behaviour and machine learning and deep learning are subsets to AI. Machine learning algorithms are AI algorithms with the ability to learn without being explicitly programmed and deep learning algorithms are machine learning algorithms in which artificial neural networks adapt and learn from vast amounts of data.

Big data

Big data is not really an emerging technology it is a field treating multiple challenges resulting from the big amounts of data collected by Industry 4.0, by the IIoT. Those challenges include capturing, storing, analyzing, searching, sharing, transferring, visualizing the amounts of...
data which cannot be processed by traditional software. However, the technologies created to overcome those challenges have to be seen key technologies for Industry 4.0.

Industry 4.0 Data Processing

Some examples for Industry 4.0 data processing are feedback loops, trending, probabilistic lifing, predictive maintenance or reliability engineering.

Additive Manufacturing

Additive manufacturing or 3D printing summarize multiple new manufacturing technologies for various materials which add material layer by layer to shape a 3D object. This stays in contrast to classical subtractive manufacturing methods removing material from a block of raw material to achieve the shape. This has multiple benefits, in particular lot-size-one and the creation of internal structures which would be not possible or immensely difficult to manufacture with subtractive manufacturing.

Digitalization, automation, robotics and drones

Digitalization, automation, robotics and drones are also sometimes considered part of Industry 4.0, even that they were core elements of the third industrial revolution [2,3]. However, the ongoing activities could be considered enhanced digitalization and enhanced automation. Moreover, the introduction of collaborative robots (cobot) allow a shared working space for humans and robots in production environments by assuring the safety of the humans by (for example) sensors. This makes the typical fences unnecessary and allows a direct interaction between human and robot, allowing that robots support humans.

Simulation and Reconstruction

Similar for simulation and reconstruction. Both were core parts of the third revolution [2,3] but simulations are becoming a core part of digital twins and it’s becoming more and more important for the fourth revolution. Actually, in the fourth revolution, simulation takes a whole new meaning by enabling real time physical actions based predictive simulations. And reconstruction leads to data which is easier for automated data interpretation.

Blockchain

Blockchains present a way to assure that data is not changed after being stored once. So, they are an ideal way to store financial transaction records or component files. This is enabled by a chain of data blocks and every block consists not only of new data but also of a hash representing the data of the previous block (which in itself contains a hash of the block N - 2, …). This already makes it difficult to change earlier blocks as the hashes in all the following blocks would have to be recalculated. To enhance the manipulation safety even further a nonce (number used once) is added to each block. A nonce is the result of a restricting rule for the hash of the following block. Meaning, there is a rule that the hash of block N (for example it has to be smaller than a certain number). Therefore, the nonce of block N-1 (which is included into the calculation of the hash of block N) has to be changed multiple times until the hash of block N fulfils the given rule. For e-currencies those rules are usually increasingly difficult to achieve to ensure the value of the currency due to the difficulty of finding a fitting nonce.

Quantum Computers

Quantum computers, like the one based on the Sycamore processor [5] are using two quantum mechanical phenomenon (superposition and entanglement) to enable a completely new way of computing. Quantum Computers use two-stage quantum-mechanical systems, like the spin of an electron, the polarity of single photons or the atomic energy levels as quantum bits or qubits. Unlike normal bits (which are either 0 or 1) a qubit is in a superposition state between the two states |0> and |1>. In the beginning Schrödinger didn’t accept the validity of this quantum mechanical phenomenon. This is why he wrote his famous paper which includes the gedankenexperiment on the cat [6]. Eventually, Schrödinger had to accept that this gedankenexperiment was misleading and accepted superposition.

The second quantum mechanical phenomenon is called entanglement and was described by Einstein as a spooky action at a distance. If, for example the quantum mechanical state of an atom is entangled with the quantum mechanical state of a photon a measurement of one of them will influence the state of the second. Even if they are separated by several kilometers. And this reciprocal influence is instant (independent of the distance). It is not limited by the speed of light, but it also cannot be used to transfer information [7].
Quantum computers are currently in the transition phase from research to first industrial implementations. For calculations they use multiple entangled qubits (53 in [5]) which are initially programmed into a certain state. By conducting certain measurements calculations are conducted, but unlike classical computers the results of all possible variations are calculated at the same time. This enables an exponential speedup of certain algorithms compared to classical computers. This leads to the fact that for example classic public key cryptography can be cracked within seconds (independent of the length of the keys). Therefore, once quantum computers become available post-quantum algorithms or quantum cryptography should be used for data encryption (and for the creation of blockchain nonces). However, quantum computers will not replace classical computers they will be an add-on for certain computational challenges.

Quantum computers are clearly emerging technology but whether they will be considered Industry 4.0 only history will tell. However, as they are a means of processing data in a new way they could be one of the tools industry is waiting for to enable the full potential of Industry 4.0.

What is Industry 4.0?

For all of the technologies described above somebody might argue that none of those technologies is actually new and there is an element of truth to those statements. So, overall what makes Industry 4.0 if not the emerging technologies. It is the integration for a purpose, that was not achievable up until now. It is the reduction of burdens, the reduction of proprietary data formats and proprietary interfaces. It is the collaboration of different players around the globe to work on the greater good. This will eventually lead to a completely new market – a market for data – and a market for purposeful application of data.

What is NDE 4.0?

The question “What is NDE 4.0?” is, like the question “What is Industry 4.0?”, not easy to answer and most people will have a slightly different view. From the naming some parallelism is indicated, and it becomes clear that NDE 4.0 is somehow NDE connected with Industry 4.0.

With the foundation of the DGZfP (German Society for NDE) committee “ZIP 4.0” in 2017, of the ASNT (American Society for NDT) committee “NDE 4.0” in 2018, and of the ICNDT (International Committee for NDT) Specialist International Group “NDE 4.0” in 2019 the NDE industry started activities regarding NDE 4.0. Also, multiple paper have been published [2,3,8,9,10,11,12] on this topic. The first DGZfP seminar on “ZIP 4.0” was April 1st 2020 and the first international conference on NDE 4.0 will be June 2021.

Most of the work presented up to the moment focused on single use cases and on the comparisons across the four industrial revolutions and the four revolutions in NDE. Most of those models neglect that both the industrial revolutions and the revolutions in NDE have a basis – handcraft for the 1st industrial revolution and human perception for the 1st NDE revolution. Figure 1 (based on [2,3]) adds this basis and shows the differences in the four industrial and NDE revolutions.

This paper goes on step ahead of the work published up to the moment and details the possible use cases. Therefore, two surveys were started. The first asking “What do you think is NDE 4.0?” and the second asking for the challenges of NDE. The results of both surveys are finally used to present the different use cases for NDE 4.0.

Survey: What do you think is NDE 4.0?

To get closer to the answer to the question “What is NDE 4.0?”, to collect different ideas / views, a survey was conducted at the short course for NDE 4.0 during the ASNT annual conference 2019 before starting the training, with 50+ in person participants. The bullet points in the following six sections represent the answers to the survey.

NDE 4.0: The Future of NDE

The following answers were quite general, identifying NDE 4.0 as the future of NDE:

- The next level
- It's a good future for the NDT work
- The next generation of NDE leading with data, automation and digitization
- Think it is just getting started but has potential
The following answers show the idea of using the emerging technologies described above to enhance the existing NDE methods. This could also be called “Industry 4.0 for NDE”:

- Information/Communication technologies coupled with augmented inspection methods
- A means to maintain and advance our craft utilizing a melding of best practices and emerging technologies
- IA, VR, Deep Learning
- IoT, Big Data, networking, etc.: Taking these components and applying them throughout the NDT industry
- Deep Learning
- Improving NDT efficiencies via modern connectivity and advanced computing
- Utilization of technical and social advancements. As technology increases so does the capabilities/possibilities. As networking, data collection/analysis/reporting, automation increase so should the influence on NDE.

**NDE 4.0: NDE – data source for Industry**

NDE has always been a central tool to assure a sufficient quality during industrial production and safety during operations. The following ideas show a potential for an increased use of the results of NDE to improve the design, the product and the production by statistical analysis of the NDE data. This could also be called “NDE 4.0 for Industry” and plays along with the wish to give NDE data more meaning.

- If we can use NDE results and feedback to improve quality of products
- Acquisition, manipulation and interpretation of data obtained utilizing NDT techniques to determine the effectiveness of a manufacturing process or application
- To increase quality and production

**NDE 4.0: Giving more meaning to NDE data**

The following answer presents the idea that NDE 4.0 should give more meaning to NDE data. An interesting challenge and an idea for the answer can be seen in two ways. Firstly, as discussed above, by using NDE data for statistical evaluation in an Industry 4.0 environment, secondly, for inspection control. Inspection control includes ideas like digital workflows for NDE, traceability, or reliability.

- The conglomeration and identification of data for use. Giving meaning.

**NDE 4.0: Data Exchange and Feedback**

The following answer goes along with the previous idea; however, it adds two additional key points: data exchange between customer and client – and an End of Life (EOL) assessment with feedback to the original manufacturer. The first point shows the desire to enable the electronic exchange of job descriptions and inspection results (using standard interfaces) and the second the desire to learn more about the development of equipment during its life. Both for giving NDE data more meaning.

- Feedback, data access to clients for production; EOL assessment of equipment

**NDE 4.0: Consequences**

The last group of answers deals with consequences which could be caused by NDE 4.0

- Eventual robots interpreting better than humans
- Human with AI will replace human without using AI

**Survey: Challenges of NDE**

As the awareness of the what is Industry 4.0 and NDE 4.0 and the awareness regarding the benefits of Industry 4.0 and NDE 4.0 is not yet pronounced in practically any industry the question was inverted. The question “What was the most negative thing somebody said about NDT / NDE ? / What are your most negative thoughts about NDT / NDE ?” was on the one hand asked in social media [3] and on the other hand in the beginning of the beforementioned short course on NDE 4.0. The bullet points in the following thirteen sections
represent the answers to the survey. Editorial comments within the answers are indicated by brackets. Those answers will give a list of challenges NDE has to take on. Part of those challenges can be solved by NDE 4.0 – and will help identifying the answers to the question “What is NDE 4.0?” even better.

**NDE: Not a Skilled Trade**

The following answers shows the perception of some other professions regarding NDE: NDE is not considered a skilled trade and on top some people even assume that NDE is causing flaws. Both might be caused by the fact that the awareness of NDE is quite limited in society, and NDE in some cases is seen as an unnecessary cost factor (as the answers in the following paragraph will show). NDE 4.0 might help with giving more value to NDE data but it will only partially be able to help raising awareness. To raise awareness the NDE community should stop internal conflicts and focus on building up a reasonable lobby to show its value to everybody, in industry, governance, society, education, and media.

- “NDE is not a skilled trade” is something I’ve heard over and over by some men in “skilled trades”.
- We don't need NDT - you only test [and introduce] flaws into the material.

**NDE: Unnecessary Cost Factor**

As mentioned in the last paragraph most of the answers are regarding one central challenge: NDE is seen as an unnecessary cost factor (up to the point that it would make the product too expensive for the market) and a production break:

- The most negative thing I've ever heard about NDT came from one of my former CEOs. I wanted to show him the NDT Department on a plant tour and he refused saying that NDT is all “smoke and mirrors”.
- Production brake
- Turnover preventors
- Unnecessary cost factor
- Its “no value added”
- Non value added [Multiple responses]
- You are like my mother in law, I don't need you... hate it when you are there... you create extra work for the rest of us and I end up paying a ****load of money
- My negative thoughts center on my company’s lack of understanding of NDT and the fact that they see it as an impediment to throughput.
- Costs money and takes time
- Expensive to use and only slows down manufacturing
- NDT is a detriment to production more than an additive value
- Costs too much
- It's all smoke and mirrors; costs too much; bottle neck; non-value-added; only represents negative issues
- Some have said it is unnecessary and has no effect on the product or companies’ future
- NDT in civil engineering: “If NDT becomes mandatory, our product will be too expensive for the market”
- NDT does not have any value at all. It only sorts out parts, that in reality are good. I don't want it and I would never ever do it, but my customer insists on it. I'd prefer spending the money into further improvement of my production!

The last of those answers shows how NDE could overcome the challenge of being seen as an unnecessary cost factor. The customer wants to improve his production. Therefore, NDE needs to help the customers achieve this goal. NDE needs to record the data and provide it to the customer so that the customer can use it to improve the production, the design and the product. This could be established by using standard Industry 4.0 interfaces like OPC UA [2,3], by enabling “NDE meets IIoT”. In the survey “What is NDE 4.0” the participants already indicated the need for such a development which could be named “NDE 4.0 for Industry”.

**NDE: NDE in Engineering**

Another group of answers shows some of the challenges NDE is facing in engineering. In some cases, NDE engineering is not included in the design phase of products either because other engineers think they have a sufficient knowledge of NDE or because they think that NDE is not needed due to safety margins. NDE 4.0 for Industry could also help here. If NDE data is seen as valuable the focus might shift to assure that the data
treasure NDE is achieved appropriately – and the statistical evaluation of NDE data will also show if the safety factors are big enough to waive NDE.

- Many times, other Engineers and project managers never include NDT Engineering in planning because they believe they know everything there is to know about NDT. Many times, mindlessly prescribing methods that cannot detect the flaws or just throwing it in after planning with even thinking. NDT Level III and Engineers should always be included in design and planning phases. This will save money on the long run.

- NDT in civil engineering: “we don’t need NDT, the safety factors in design will cover any flaws (and probabilities will cover any uncertainties)”

- NDT in civil engineering: “your xxx is not good enough to detect yyy, so I won't use it for zzz” (look for the logic)

**NDE: Hard to Explain**

If non-NDE engineers would know enough they would easily see that the specialist knowledge of an NDE engineer is key. It needs a fundamental understanding of the inspection technology, of the physics and of the detection mechanism. This fact also leads to the fact that some people are quite intimidated by NDE or even don’t believe in the results.

- It is sometimes hard to explain the benefits to non NDE people
- Technology is too "Star-Trekky"
- For UT & ET: Still black magic
- My negative thought would be that NDT needs better distribution of education and understanding to the public
- Disbelief that UT is finding defects

**NDE: Human Errors**

The high number of parameters and the low level of automation leads to highly complex inspection situations for the inspectors. Therefore, human factors have to be seen critical for NDE. NDE 4.0 will help by increasing the automation level of inspection and data interpretation and assuring revision-safe storage.

- Too many operator variables
- Based on operator guess
- Operator dependent
- Consistency between inspectors to interpret the signals
- Human error included in process
- The most negative thing I have heard is there is too much variance potential in interpretation of results from person to person. This causes question of the reliability of the results. I agree with the statement.
- Human factors are very important in risk-based management

On a side note: even that the inspection related human factors are reduced due to automation, some programming related human factors might be introduced.

**NDE: Reliability**

Inspection reliability consists of the reliability of the method mixed with the human factors. And the proper determination of the reliability, of the PoD (Probability of Detection), of the IoU (Intersection over Union), will get even more crucial once NDE data is being used for Industry 4.0 data processing, like probabilistic fracture mechanics [13].

- Only finds ghosts
- Difficult to eliminate false positives
- Find unnecessary defects; not proven
- Didn't predict a failure
- Risk outcomes for miss-calls in NDE are higher, making it more responsible and skill critical field whether its Aerospace, pipeline, or refinery work.

**NDE: Lots of Data**

What will be a huge benefit for Industry 4.0 in the future is currently a challenge for NDE: some NDE methods create file sizes of several gigabytes which leads to the fact that NDE inspectors have to analyze lots of data.
For sure this can be simplified by reconstruction technologies, AI and simulation. And the solution of the big data challenges will help NDE on top.

- A lot of information to analyze

**NDE: Very Conservative**

The NDE business must assure the quality of components / assets. Therefore, the trust in the inspections needs to be build and finally the best-practices need to be standardized. This are some of the reasons why the NDE business is conservative and makes advances difficult to achieve. This will also be a challenge for the introduction of NDE 4.0. However, NDE 4.0 could also be the means, by collecting and analyzing the data, to show easier that a new technology earned its trust.

- My negative thoughts for NDE are that compared to other fields such as medical, automotive, etc. it is not on par in advancing as quickly as technological advances become available.

**NDE: Methods**

A different challenge of NDE is shown by the following comments:

- Do not always have technology to find what we are looking for.
- Operational hardship in military field application
- Reference [knowledge base or access] is not up to the mark

There is not always a technology available / existing for the asset to be inspected. This is in particular true in environments were not all the existing technology is available, for example in (military) field application. However, in some cases it could also be caused by the variety of methods and not every NDE engineer / inspector being an expert in all methods or not having a sufficient access to new developments or in general to a knowledge base (references).

**NDE: Inspector Training Regarding Manufacturing Methods**

Similarly, for a good interpretation of the NDE data an NDE inspector needs a basic knowledge of the manufacturing method of the asset under examination and of the key processes leading to potential material imperfections. Here algorithms / AI should prove helpful leading to the situation that inspectors with AI will replace inspectors without using AI as already mentioned in the paragraph on what inspectors think what is NDE 4.0.

- Lack of
  - process knowledge
  - Surface preparation
- So many NDT inspectors who have not enough experience and little knowledge of welding making false calls

**NDE: Customers Influencing/Questioning the Results**

A proper inspection is key the guarantee the quality necessary for an asset. However, with NDE being seen as un unnecessary cost factor and with non-NDE personnel not sufficiently understanding the value of NDE it can come to situations that customers start questioning the results of the inspections or even that they start trying to influence the inspectors. NDE 4.0 will help by providing arguments by data showing the need and the success of NDE.

- Refused to believe or understand what test was telling them. Test not valid.
- Why don't you inspect at a different location?
- Perform the spot test at a different location
- You mustn't look for indications in area you expect defects.
- You can use another method, then the findings are acceptable.
- I got the "the other inspector never rejected anything, why are you rejecting so many pieces" guess something in the process changed is what I said.
- The amount of welders who somehow think you have a magic pen for putting defects in radiographs is astounding. "That wasn't there when I welded it!", says the welder with the X-ray vision!
- You don't need any inspection until something goes bang. Always chuckle when a welder tells you that they have never had a weld rejected. Two types of welders out there. There's those that accept that there's always a chance a weld will dip and there's those that tell a lot of lies.
**NDE: Ethics / Inspector Mentality**

The next step after simple influencing of inspectors might be bribes. This can bring inspectors into ethically difficult situations. However, also some inspectors / employers are trying to take shortcuts in training, certification and inspection procedures. NDE 4.0 should help by tracking the inspections, recording and visualizing the inspections performed.

- Got offered something off the breakfast menu at McDonald’s for me and my helper once on a turnaround. It was insulting because it was the ugliest weld I had ever seen on a 18in pipe and it was to 31.3 Severe Cycle too. It wouldn't have been as insulting had I been offered the dinner menu at least... Either way they had to cut it out cuz I don't do bribes.
- Lack of ethics
  o in certification / qualification / training of technicians
  o in the application of test procedures
- I don’t inspect chips
- Why do we need to inspect parts when we never find indications?

In particular the tendency of humans and inspectors to not perform tasks which seem unnecessary to the individual can be critical of the data is to be used for statistical evaluation in connection with Industry 4.0 evaluations. In such cases those not inspected areas could lead to data which has limited significance.

**NDE: Compensation**

Job compensation, in particular in areas requiring responsibility, needs to be adequate to prevent persuasion or even bribes. Moreover, it seems to be an issue that the regional differences are dominant.

- Compensation tends to be dynamic per region versus static per method/experience/level/market availability of those methods (i.e. not a lot of certified ET III tubing inspectors)

**NDE: Traceability**

None of the answers was regarding inspection traceability – even that this might be a key challenge of NDE – ensuring that the correct component was inspected, that the results are connected with the appropriate component, that the results are stored revision-safe and that the results are easy to retrieve in a digital manner.

This is an example of uncovering unknowns that people are unaware of.

**Non-Technical Challenges**

Data compiled and reviewed from series of focused discussions on the topic indicate in addition the following challenges:

**Leadership**

There are several reasons holding executives back from taking steps to create innovation-driven differentiation and change their destiny. First is the Management Incentives. The annual bonus programs promote data-driven incremental improvements. Initiatives such as Six Sigma and Lean, which help with productivity and quality, have stifled creativity for many companies. The promise of predictable near-term profit is a trap that so many managers still fall in, trading off larger intangible gains in the future for marginal visible gains in the ‘here and now’. NDE 4.0 is a long-shot game, requiring serious investment in technology and skills development.

Second, Companies tend to be excessively risk averse, rightly so. They focus a lot of energy on “what” (metrics) and “how” (process), and more recently, “why” (purpose). Organizational consultant and writer Simon Sinek puts these in the so-called Golden Circle [14]. However, adaption of Industry 4.0 innovation requires a little different twist to the golden circle. Innovators start with “Why not?” and then go on to “How about?” and “What if?”

Third, the management consultants who lead change initiatives and business school professors who publish bestsellers based on large amounts of data analytics generally provide valuable insight into successful companies; unfortunately, all in hindsight. The book Good to Great [15] became very popular in early 2000. Yet the growth model in 21st century has been very different, which is now captured in the book The Four [16].

The fourth industrial revolution requires a new style of leadership, that can tackle the issues surrounding people in *people-machine integration*. These leaders are digitally competent who can take responsibility of the people-
side of this massive change; providing a clear direction and management in an open and transparent, employee-centric environment. This is also termed as Leadership 4.0.

Effective digital leaders in industry will be responsible for continuously changing interaction between technologies, machines and people, whilst nurturing ongoing knowledge-sharing, competency development, collaboration and innovation. They will need to mirror the technology of Industry 4.0 and IoT in that connectivity is at its core. Some call is Connected Leadership for that very reason.

Skills and Competencies

The organizations need a whole new skill set. Skills around Information and Communication Technologies (ICT not just IT), coworking with intelligent systems, (desktop as well as industrial Cobots), and more importantly willingness to accept that what you know today will likely be obsolete before you can establish yourself as an expert. The need and speed for learning in the 4th revolution is an order of magnitude larger than the previous revolution. Employers and employees both need to take the learning and development as shared continual investment. While operators will need training on technology, the managers need to get on top of the processes, and leadership ought to explore new business models. The skill to rapidly learn and develop new skills will be the key. From within Industry 4.0, the AI reduces the need for operator technical training, augmented reality is enhancing training experience, and the cobots can be programmed in real-time through on the job execution.

Management Processes

Over the years, consistent focus on productivity improvement for near term profits has dampened the ability of companies to rapidly explore new space and create new products, or technologies or even exploit possible synergies across existing technologies. A very common workplace phrase is “we could do so much if we can get away from fire-fighting.” Exploration requires a bit of risk taking and investment along with a process that helps continuously assess and mitigate that risk. The term “Fail fast” or “Failure is a learning opportunity” requires a structured approach to work with. This is different than hit and trial. This will be discussed later.

Technology Solution Providers

Industry 4.0 has brought about a business opportunity for a lot of technology solution developers, who may not fully appreciate the methodology, purpose, and intricacies of NDE. These solution providers are motivated to force fit what they sell to any customer they can have access to. Since, you may get approached by different providers with so many diverse options, you need an appreciation of what is a better fit and when. Lack of awareness around the technology, and uncertainty associated with continuously change makes it very hard for management to decide where to invest.

NDE 4.0 Use Cases

The last paragraphs showed on the one hand what people in NDE think that NDE 4.0 is about and on the other hand it presented several challenges of NDE which NDE 4.0 might help to solve.

The answer to the question “What is NDE 4.0?” goes in parallel to the answer to the question “What is Industry 4.0?” addressed above.

Industry 4.0 and NDE 4.0 require that burdens for digital communication are lowered, proprietary data formats and interfaces opened, and semantic interoperability implemented. This allows to combine technologies from different manufacturers and different industrial sectors. This allows manufacturers to focus on their core-knowledge which will finally result in better products which are more competitive. This allows NDE to become part of the Industry 4.0 world and to use Industry 4.0 measures (like the once described in the beginning of this paper) for NDE. This allows NDE and Industry to grow together as shown in Figure 1.

The surveys and the gained understanding about the “What is NDE 4.0?” helped identifying three main groups of use cases for NDE 4.0: Industry 4.0 for NDE, NDE for Industry 4.0, and NDE awareness and Table 1 presents an overview of the different use cases and their connection to the challenges.
Industry 4.0 for NDE

Enhancing NDE Methods by Emerging Technologies

The most obvious use case for using Industry 4.0 for NDE is the usage of the emerging technologies connected with Industry 4.0. This includes the use of cloud computing and storage, 5G, augmented reality, artificial intelligence, big data, additive manufacturing, digitalization, robotics, simulation, reconstruction, and blockchains. There is not a single Industry 4.0 emerging technology which does not enhance the existing NDE methods. It just differs case-by-case which ones to choose.

Table 1 The cross correlation between the use cases identified and the answers on the surveys “What do you think is NDE 4.0” and NDE challenges. Here “X” symbolizes the cross correlation and “C” that a certain challenge might be critical for a use case.
Improving NDE Equipment using Feedback

The use case to improving NDE equipment using feedback wasn’t mentioned by any of the answers of the surveys and from several personal conversations it seems that the NDE hard- and software manufacturers currently do not see the big value within this use case. The idea is simple: by providing data like error codes, system parameters, system status information, or software exceptions/errors back to the manufacturer the manufacturer could use the data to improve the NDE equipment, the NDE systems, or the NDE software by statistical evaluation of the data. Also, the statistical evaluation of user behavior might help to improve the equipment in terms of for example usability.

Inspection Control

The third group of Industry 4.0 for NDE use cases are based on controlling the inspections and they have multiple aspects to them.

Component traceability means that it needs to be ensured that the correct component was inspected, that the documentation is revision-safely stored, and that the results can easily be retrieved. Revision-safe data storage can be implemented by using blockchains and the component identification by digital component files and electronic component identifiers.

Digital workflows allow to perform transfer job descriptions (including the specifications to be applied) in an electronic way all the way from the customer to the inspection personnel and the results are transferred back to the customer. Those data transfers should be performed using IIoT technologies and interfaces (and not by, for example, the transfer of Excel files or PDFs using email or USB sticks).

Digital commissioning goes one step further by also transferring the order-related information using standard IIoT interfaces.

Result statistics and feedback loops on destructive tests, component acceptance, later service inspection results and EOL (End Of Life) component testing helps inspectors and other quality assurance personnel to get a better feeling of the value of the inspections.

Such result statistics can also be used to get a better view on the reliability of certain inspections.

Usage statistics or inspection performance evaluations can on the one hand show the need for a certain inspection and on the other hand it can identify differences by parameters like time of day or inspector. This should help with operator dependence and inspection consistence.

Such evaluations can also be used for automatically monitoring training and experience hours for personnel evaluation, qualification and certification.

Overall inspection control will help proving and visualizing the value of NDE which should help the complete NDE industry.

NDE for Industry 4.0

Data transfer and storage

The NDE for Industry 4.0 use cases, as identified above, start with data transfer using standardized Industry 4.0 interfaces. “The NDE sector will not succeed in giving the industry new interfaces. It is more reasonable to use the Industry 4.0 interface developments and to participate in the design in order to shape them for the NDE requirements.” [2,3]. Once the data is transferred using standard interfaces it can be stored in digital twins, in data-base systems, or in clouds. Moreover, in the case of in-situ inspections during manufacturing or operation with for example ultrasonic sensors (like vibration analysis or acoustic emission) and optical sensors (like IR, UV, visual) a direct feedback for production or operation (SHM: structural health monitoring) gets possible.

Basis for using the data (both in-situ or ex-situ) is semantic interoperability so that computer systems can understand the data.

Data evaluation

This digital understanding of the data leads to the actual use cases for NDE for Industry 4.0. By statistically analyzing the data, by identifying cross-correlations with other data NDE results/data become a valuable asset. This asset can then be used for
• feedback loops for production and design
• trending to assure a constant or rising production performance
• probabilistic lifing methods to calculate the life of components more accurately [13]
• predictive maintenance to calculate the necessary maintenance inspections more accurately
• reliability engineering to enhance the reliability of components and products.

NDE in Additive Manufacturing

Components manufactured additively are usually difficult to inspect due to their complex internal structures or complex external shape. This is why the usability of most of the traditional NDE methods is very limited for those components. In most cases, out of the traditional methods, only computed tomography works.

This is why several groups started working on in situ NDE methods monitoring the signal during the additive manufacturing process. The most frequently used sensors are optical sensors monitoring and recording the infrared, visual or ultra violet light and providing feedback loops. With the acquired data the internal and external dimensions of the components can be measured. Moreover, the heating and cooling processes, the melting and freezing processes, and the expansion and shrinking processes can be monitored and corrected.

Therefore, those kind of inspections are good examples for the benefit of NDE for industrial application and how NDE 4.0 can improve the production process.

NDE of Drones and Critical Industrial Robots

Very soon, humans will be in era where drones performing everyday functions will need inspection and maintenance programs. For most part, the society reacts to problems when they show up. It is not hard to imagine that one day in near future, a package delivery drone will have a catastrophic failure in someone’s back yard, and new regulations will emerge around NDT of aging drones. And industrial robots on similar way. This technology and application is so new that it is hitting obsolescence before aging.

NDE Awareness

All the use cases described above will eventually lead to an improved awareness about NDE. This will help to complete NDE sector and it will help to increase the value people see in NDE.

Safety 5.0 – The Purpose of NDE 4.0

Assuring safety is the number one motivation behind infrastructures inspection and maintenance. Everybody wants the system to function reliably, whether it is air, water, or a ground transportation vehicle; a material or energy manufacturing plant; a bridge or a building, an appliance or a piece of an equipment, and more. Everyone wants safety of all customers, users, stakeholders, operators, construction and maintenance crews, as well as the inspectors.

To begin with, most digital systems offer a clear advantage over traditional system in terms of accuracy and speed. However, a significant contribution of Cyber-Physical NDE system (NDE 4.0) stems from the better control or total elimination of human factors. Having developed techniques to quantify human factors in NDE-POD studies [17,18], author has a first-hand appreciation of value NDE 4.0 in context of system performance. This leads to a more reliable inspection system, i.e. better Probability of Detection (POD) and a more consistent POD from inspection to inspection. Ref Figure 3. Virkkunen et. al. [19] have shown that using sophisticated data augmentation, modern deep learning networks can be trained to achieve superhuman performance by significant margin in ultrasonic inspections. This improved and dependable POD provides enhanced safety, and enables optimization of inspection programs reducing life time operating cost of an asset. The structured management of life time digital data, like a digital twin, opens up additional economic opportunity to asset manufactures and operators.
All technologies discussed earlier have opened up many new possibilities and even a whole new paradigm; where NDE 4.0 provides an opportunity to advance all three - quality(safety), speed, and cost, as compared to the traditional perspective that you can only choose two out of the three [11]. That is why it is called the next revolution.

NDE 4.0 opens up the possibility of asset customized prescriptive maintenance, which can significantly improve the value derived from Data Analytics Maturity Model, originally proposed by Gartner in 2012.

- Analytics Level 1: Descriptive – What happened?
- Analytics Level 2: Diagnostics – Why did it happen?
- Analytics Level 3: Predictive – What will happen?
- Analytics Level 4: Prescriptive – What should we do?
- Analytics Level 5: Cognitive – What don’t we know?

This combination of Stakeholder Safety and Economic Value can be summarized under a single term Safety 5.0, shown in Figure 4, on lines similar to the definition of Society 5.0 which brings economic value and social benefit through cyber-physical confluence.

Figure 3 Industry 4.0 Capability has the potential to provide a steeper asymptote to a POD of 1.0 as compared to Intrinsic Capability or System Reliability

Figure 4 Safety 5.0 as value proposition for NDE 4.0
**Potential Approach to Adaption**

Next step to awareness is adaption, which requires a roadmap, a process, and skills set, in addition to financial capital. Let’s look at each one of them.

**Adaption Roadmap**

An aspect to appreciate is that the revolution is not a discrete event that happens overnight. The digital technologies all emerge independently and then interdependently, and one day, a very different value proposition becomes apparent. The same is true for any organization. Various technologies discussed earlier need not be adapted all at the same time from technology value perspective. Nor is it affordable to do so from cash and talent perspective.

Every business on a path to digital transformation needs a roadmap of what to adapt, when to adapt, and for what purpose. The roadmap needs to be aligned with market capture strategy on downstream side and talent/knowledge acquisition on the upstream side. The time span for roadmap is likely to be 7-10 year vision; 3-4 year strategic plan, and a 12-month tactical plan with allocated budgets. The attitude should be like a weather forecast. Hi fidelity and confidence for the near term, and a band of uncertainty for the far term; all of which needs to be actively managed with every passing quarter.

**Process for Ideation to Monetization or Value Realization**

Standard and reliable process can reduce pain in all aspect of NDE 4.0 adaption cycle. From Market perspective, it provides guidance on how an organization can fulfil unmet inspection and safety needs, enhances the competitiveness of organizations, NDE products, and inspection services, leads to the easier acceptance of global inspection products, and reduces time to market for new inspection equipment. From an organizational perspective, it increase the ability to make decisions: test and try, fail fast, capability to take reasonable risks, facing challenges and uncertainty associated with NDE 4.0, evaluate the progress of the organization and identify and share good practices in innovation management, and share a globally accepted ‘common language’ for innovation management and perhaps develop a common language for NDE 4.0

**Simplified Approach**

Innovation process for NDE 4.0 can be described as a series of connected steps, which leads to a new NDE product, service, or a business model. Successful outcomes typically require an innovator to make assumptions at each step, validate or challenge them at the next step, go back if required, continuously build upon new learnings, and iteratively closeout on the purpose.

In its simplest form, the development project is about visualization of the end application, starting with a lot of ideas or opportunities; screening them down to a few projects; and then ethically executing them to a successful delivery or a new learning, sometimes; as shown in Figure 5.

![Figure 5](image.png) Structured approach to innovation in context of NDE 4.0

**Market Insight**

The first major step in NDE 4.0 is to define a problem worth solving. The beginning of an innovation process is always very hazy. It is generally an accidental or deliberate matchmaking between an idea and the problem it can solve, sometimes difficult to separate, which came first.
When the objective is to take a new product or a service to the market, then there is a need for a good insight on what opportunities exist out there and what are we competing against. This market place insight is an absolute must to fulfill any desire or purpose to influence it. The previous sections have highlighted a number of opportunities and ‘negatives’ that NDE needs to address.

NDE systems have two primary customers, inspectors and owner/operators—both looking for zero job pain, at times conflicting with each other. The inspectors would like a system that is easy to learn, set up, carry, and operate, something that is physically comfortable: ergonomic, weather-proof, clean, with no messy consumables. The operators or business owners, ideally, want no inspections, but inspections are something they must live with for safety assurance. So, they want minimum downtime, maximum intervals between inspections, and minimal cost of equipment, consumables, and so on. Both users want reliable and decisive information.

Complementary step is to see what already exists or is in works to solve the problem you have identified. Once again, there is generally a competition, or an incumbent solution resisting change to start with; and if you make it will invite new competitors to the market.

**Structured Ideation**

This is the most creative and elusive step of the innovation, and generally supports the myth that you can’t teach innovation, or innovators are born. Ideation may not be science, but it is certainly not a magic. It is probably an art, and sustained practice gets you to a state of mind that is continuously generating great ideas. Experience has shown that the ideas are not a random occurrence, but rather triggered by some form of an intellectual stimuli. Which implies that 100s of ideas can be generated by using a stimulating environment or an exercise. Quite often, an ideation session can lead to new markets, in addition to serving a specific predefined objective. Invariable it must start with an objective. Typical Ideation objectives within NDE 4.0 will be of the following form.

- What can AI or VR do for inspection systems?
- Which is the technology can solve the ‘elusive problem’?
- How can we make inspection activity safer for the inspector?
- How can we accelerate NDE by 10X?
- What do we need to reduce certification levels for certain inspections?
- What lack of technology will make us irrelevant in 5 years?

**Purposeful Qualification**

After a couple of iterations between customer problem and solution ideas, you get to stage of assessment of their worth. I submit a need to address these 3 questions:

**Value Proposition:** Does it add value to a customer/user/consumer? A good value proposition acts as a pain reliever and/or gain creator for a job to be done by a prospective customer. In this case it is the inspector and the asset owner/operator.

**Purpose & Ethics Check:** Does it fit your self-defined purpose and self-imposed ethical standards, in additional to being legally compliant?

**Concept Qualification:** Can you deliver it profitably, to sustain or grow your own business? Is it dependable, defendable, scalable, sustainable, and whatever else as a part of your purpose in the short or the long run? At times, you may have to iterate on a value proposition to qualify the idea.

**Creative Execution**

A qualified concept now needs to be converted into reality. Most companies have some form of an R&D project management, or phase gate process to continuously reduce the execution and market risk. Depending on how far out, your innovation is from existing knowledge and experience, you need to be prepared to iterate on value proposition and execution options. The ability to learn and adapt is still the key to successful innovation.

The simplified ‘ideation to monetization’ innovation value chain, described in this chapter of the book can be used on routine basis to address the growth needs of an organization or as a core execution engine in any of the NDE 4.0 applications. The steps will be iterative, more often than desired. It takes a bit of a practice to get good at it.
Value Chain is a Multilayer Filter

This activity from ideation to monetization is like a multilayer filter. At each step, you remove the options that may not work. Typically, out of 100s of ideas only handful will qualify for execution. At this stage, you could either create a portfolio of projects, or use a criterion for prioritization.

Marketing folks might see this as a funnel. Which is actually a bad metaphor because in a funnel everything that gets in from the top gets out at the bottom. In a well-designed filter, only the desired material comes out. In case of innovation value chain, the filter design is innovation management processes and the human mindset.

ISO 56002:2019 Innovation Management System – Guidance

ISO 56000 series of documents on innovation management guidance can be used for conception, development, validation, and pursuit of purposeful NDE 4.0 applications. ISO 56002 [20] document provides guidance for the establishment, implementation, maintenance, and continual improvement of an innovation management system for use in all established organizations. It is applicable to NDT equipment manufacturers, service providers, training houses, and asset owners responsible for infrastructure safety. All the guidance within this document is generic and intended to be applicable to all types of organizations, regardless of type, sector, or size; all types of innovations, e.g. product, service, process, model, and method, ranging from incremental to radical; and all types of approaches, e.g. internal and open innovation, user-, market-, technology-, and design-driven innovation activities.

Relevance: This is an overarching document that integrates all of the remaining ISO 56003-08 documents on innovation, which refer and eventually feed into for successful execution. It does not describe detailed activities within the organization, but rather provides guidance at a general level. It does not prescribe any requirements or specific tools or methods for innovation activities. This intent makes the application as broad as possible, including NDE 4.0, which also subjects the user to differences in understanding and interpretation. It is directly relevant, with some level of understanding of the overlap across fundamentals of NDE and basics of Innovation.

Skills Development

Most people view Industry 4.0 as a job killer. Every past industrial revolution has created more jobs, but with different skill set requirement. Same will be the case this time. It is not a jobs question. It is a skills question. Jobs will be there. Your current skill set will be obsolete.

From organization perspective, this includes Leadership 4.0 skills, Industry 4.0 skills, as well as an open mindset which strikes a balance across exploration and exploitation. Individual talent development plans need to support the technology adaption roadmap. There are a number of MOOCs (Massive Open Online Courses) and university certification programs that can be leveraged. Talent development needs to be viewed as a shared investment by employee and employer to make it work for both parties.

Discussion and Outlook

This paper has addressed multiple aspects to the question “What is NDE 4.0 and what are its use cases”. Like with Industry 4.0 the answer is not easy or straightforward. The use of all the emerging technologies for NDE (“Industry 4.0 for NDE”) is a major use case. However, like with Industry 4.0 it might be argued when is this sufficient to call it NDE 4.0. The other two major use cases identified are “NDE for Industry 4.0” and “NDE awareness”. All three uses cases show that Industry and NDE are growing together with the fourth revolution.

There is still a long way to go. Once the barriers to digital communication are lowered, once proprietary data formats and interfaces are replaced, once semantic interoperability is natural it will be possible to combine the emerging technologies. It will be possible to combine technologies from different manufacturers. It will enable manufacturers to focus on their core-knowledge which will finally result in better products and superior services.

Perhaps there may not be a single discreet event that defined the cross over to NDE 4.0. The first instance of digital twin based full loop cyber-physical integration can be considered as a start of the journey, and perhaps when more than 50% of the decisions are taken by the machine, one could claim adaption.

Given the challenges and opportunities, the NDE 4.0 needs collaboration on an international scale, without burdens or old structures. Ideas like NDE-manufacturer based clouds are the use of emerging technologies for
maintaining the old structures. This will eventually not work. Opening up, collaboration and the willingness to innovate are key to NDE 4.0 and will decide on the future of individual companies and of the NDE sector in total. If taken on accurately this will lead to a completely new market – a market with huge potential for NDE – a market for data, and purposeful use of data.

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