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Welcome to

The World of NDE 4.0

Let the Journey Begin

Ripi Singh
Johannes Vrana

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Foreword by Prof. Dr.-Ing. Bernd Valeske

Dear Reader,

"The World of NDE 4.0" – the title of this book – promises to be an exciting read. The two authors take us on a curious and inspiring journey towards new worlds, one could also say. This book offers a visionary and inspiring look into the future of non-destructive detection, evaluation, and condition prognosis of all products in our digitalized industry and product driven world. Sensors, data, condition detection and prognosis are taken to a new level in "The World of NDE 4.0" and allow completely new strategies and service offerings in the highly interdisciplinary field of non-destructive condition assessment of materials and products.

After more than almost a century of continuous accompaniment of industrial progress, NDE is currently experiencing a revolution, one could even say a disruptive leap in development, characterized by a completely new understanding with regard to role and system philosophy, which will determine the field of NDE 4.0 in the future. This book has succeeded in describing this paradigm shift in the world of NDE 4.0 and explaining its immense breadth in an excellent and comprehensible manner.

What may once have begun as science fiction for many has now become a realistic future scenario in the concept of NDE 4.0. Anyone involved in the world of non-destructive condition assessment at any stage of the material and product life cycle, whether as a researcher, developer, user, or service provider, will be able to discover these new worlds with the fundamentals presented in this book. The concepts and philosophies presented offer a fascinating journey into the all-encompassing NDE 4.0 system.

Anyone who wants to explore and help shape the future of NDE will be well served by this book. Engineers, scientists, and companies will gain insights for the further development and profitable design of their own working environment and the description of their own future strategy around NDE 4.0. In addition, there is helpful information regarding corresponding offers in the context of Industry 4.0.

I encourage you to enter this exciting world of NDE 4.0. It is worth embarking on this fascinating journey and, with this book, you will be excellently prepared.

Enjoy your reading!

July 20, 2021

Prof. Dr.-Ing. Bernd Valeske
Fraunhofer Institute for Nondestructive Testing IZFP
Chair of German Expert Group NDE 4.0 of the DGZfP

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Preface

WELCOME TO THE WORLD OF NDE 4.0!
— JOHANNES VRANA

This book is here to inspire NDE leaders and community to address the next revolution in Nondestructive Evaluation – **"NDE 4.0".** After the technology focused definition of Industry 4.0 from Germany, Japan defined the term Society 5.0, which calls for technology to drive the economic development and social solutions together. In some sense, it defines the purpose of Industry 4.0. On similar lines, the purpose of NDE 4.0 can be defined as "*Safety 5.0 – To concurrently Enhance Safety and Bring Economic Value to stakeholders of the inspection ecosystem.*"

System level integration of digital technologies such as machine learning, extended reality, artificial intelligence, and automation will create a platform, where specific applications can evolve to make inspections more reliable and cost effective. Just like a smart phone; where the integration of Wi-Fi, processor, memory, GPS, camera, display, and a bunch of other sensors has completely changed the world in 10 years, in ways that were not originally perceived. Such is the exponential power of digital-physical integration. We cannot predict all the changes, but we must prepare and work through the challenges associated with technology integration and adoption.

Digital transformation of the inspection systems is inevitable. Pursuit of this opportunity amidst uncertainty makes "*a well-defined purpose*" and "*robust process*" essential. This book provides an overview of the purpose of NDE 4.0 (why?), underlying technologies (what?) and ways to overcome the challenges (how?) to successfully pursue confluence of emerging digital technologies with the evolving physical world of inspection

1. Introduction to NDE 4.0

*THE FOURTH INDUSTRIAL REVOLUTION WILL AFFECT THE VERY ESSENCE OF OUR **HUMAN EXPERIENCE**.*
— KLAUS SCHWAB, CHAIRMAN WEF 2016

{ From Ripi's heart } One fine morning in June 2018, I got an email from Claudia Kropas-Hughes of ASNT. She was asking if I would be willing to work with Dr. Vrana on my proposal to organize sessions on NDE 4.0 at the upcoming ASNT Annual Conference. Apparently, Johannes had submitted a similar proposal, and from the ASNT perspective it was the right thing to do. I accepted it with a bit of skepticism, despite my positive experiences in collaborating with Germans over the past 25 years. We had a couple of planning emails that broke the ice, and we met in Houston in Nov 2018. We organized the first panel discussion on NDE 4.0 and made several changes on the fly. After our sessions were over, we went downtown for a happy hour. We discussed many things, and I felt we had different perspectives on almost every aspect we touched, including, what is NDE 1.0. Yet surprisingly, we were able to converge on whatever appeared right, as smoothly as the beer we were enjoying. What was common was willingness to listen, consider other viewpoints objectively, ideate, and build on each other's perspective, without sense of ego or ownership. My trust in Johannes shot through the roof, and I thought I like this guy. That was the start of a collaboration that has been getting stronger by the day and we have made many new friends around the world. Now, I can look back fondly and relish that turning point in my innovation practice.

Together, we got down to rethinking NDE 1.0 and many more aspects of "**The World of NDE 4.0**" at the intersection of Industry 4.0 and NDE. We just wrapped organizing the first international conference on NDE 4.0; an association that started with a one-hour panel.

History of Industrial Revolutions

For millennia, we lived using animal and human muscle power, hand tools, and mechanical levers – to help with construction, transportation, defense, and farming, as primary occupations. Over the last three centuries, humanity has seen significant change in lifestyle, driven by industrial revolutions. At this time in our history, we are going through another revolution, in which physical objects and assets are getting connected with their digital counterparts through the internet of things, creating smart products, processes, and even factories. Machines are beginning to learn and assist our cognitive functions. Small handheld devices are gaining the indispensability of a life support system. And so on. So, how did we get here?

The **first industrial revolution** began in England in the second half of the 18th century and brought about a change from handcrafted forms of production to the mechanization of production with steam engines or regenerative energy sources such as water. Transportation started to change in early nineteenth century with steam locomotives.

The **second industrial revolution was** triggered by electric power. It enabled new industries such as the chemical, pharmaceutical, and mechanical production engineering. It began at the end of the 19th century and led to the introduction of the assembly line (in 1870, the first conveyer at Cincinnati slaughterhouse, in 1913 at Ford for automotive production) and to new forms of industrial organization.

In the second part of the 20th century, the development of microelectronics, digital technology and computers ushered in the **third industrial revolution**, which allowed automated control of industrial production and revolutionized data processing in offices (computers, laptops) as well as in personal lives (mobile phones and game consoles).

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2. Purpose of NDE 4.0

AN EXTRAORDINARY BUSINESS STARTS WITH EXTRAORDINARY PEOPLE
*EXTRAORDINARY PEOPLE START WITH A **PURPOSE**.*
— JESPER LOWGREN

{ From Ripi's past } When I was working on simulating structural failures in the 1990s, I had a certain market opportunity in my field of view. A few years down, I began to feel stagnated and started exploring adjacent opportunities, which appeared to be disconnected from my experience at that time. Then one day I redefined my purpose to be *aviation safety*, and the opportunity suddenly turned out to be much bigger. I ventured into risk-based inspections, life cycle management, decision making under uncertainty, human factors; all with structural simulation as the centerpiece and innovation as a focused process. Then it all started coming together, which has now morphed into *NDE 4.0 for safety and economic value*. That is the power of a purpose.

Thought leaders and successful disruptors show us that in this fast-changing world, the best way to stay relevant is to have a purposeful business. It helps continuously re-align value propositions because the focus is not on tasks, projects, initiatives, or fiscal objectives. It is a lot easier to step into new territories, and more palatable to digest the failure of an effort, when the eye is on a bigger mission than tangible SMART goal (Specific Measurable Achievable Reasonable and Time-Bound) goal.

Purpose helps redefine the playing field, because it assumes a lot less, has fewer boundaries, and opens the mind.

The traditional view of the mission statement is to align the organization in terms of priorities and focus, creating efficiency and

effectiveness, engaging employees, and retaining customers. That is not enough. When you upgrade your thinking from mission to purpose, you also upgrade alignment to trust in relationships with employees and customers.

This chapter discusses several use cases or value propositions from digital-physical NDE 4.0 and builds up to the purpose of NDE 4.0 (the why?). In chapter 3 we will sketch the inspection ecosystem with stakeholders and value streams, and then connect them with the use cases.

NDE 4.0 Use Cases and Value Propositions

NDE 4.0 is all about the purposeful physical-digital-physical loop. We all have seen digital technologies and physical methods continuing to evolve, mostly independently and sometimes interdependently. The real power is in the concurrent design of inspection systems through an application of digital twins. These provide an ability to capture data directly from the materials and manufacturing processes to usage and in-service maintenance, across multiple assets. The data can then be used to optimize maintenance, repairs, and overhauls over the lifetime of an asset, and even feed it back to the Original Equipment Manufacturer (OEM) for design and production improvements.

If data is the new crude oil, then NDE 4.0 is the new oil rig.

We took a design thinking approach to first capture end user pains and perceptions, through two surveys. The details and outcomes are discussed in an article published in the Journal of NDE[12]. One thing that became clear and provided us the incentive to write this book is that the digital technologies can address several performance challenges ...

[12] NDE 4.0 – A Design Thinking Perspective; J Vrana and R Singh; J Nondestruct Eval Vol 40, 8; 2021.

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3. Inspection Ecosystem

*WIDENING YOUR MINDSET ABOUT ECOSYSTEMS ALLOWS YOU TO **IDENTIFY KEY-VALUE CHAINS** WHICH WILL BENEFIT YOU.*
— AGILEJOURNEY.NL

{ From our shared journey } In April 2020, we felt the need to look at NDE 4.0 in the context of Covid-19. We reached out to ASNT and DGZfP members on the NDE 4.0 committees and a few of our international supporters of NDE 4.0. The conversation quickly turned into what is important. As we went around the zoom-room, it became apparent that we had diverse backgrounds and varied requirements to sustain our individual organizational interests. Although everyone in principle agreed to a higher purpose of NDE 4.0 in terms of safety and economic value, each one of us were looking to get to some specific solutions in their context. We also realized that we still need to work together for NDE 4.0 to deliver to its performance. We realized we need to look at the NDE as an ecosystem, wherein every stakeholder must see a value proposition from their vantage point, in whatever value stream they belong to.

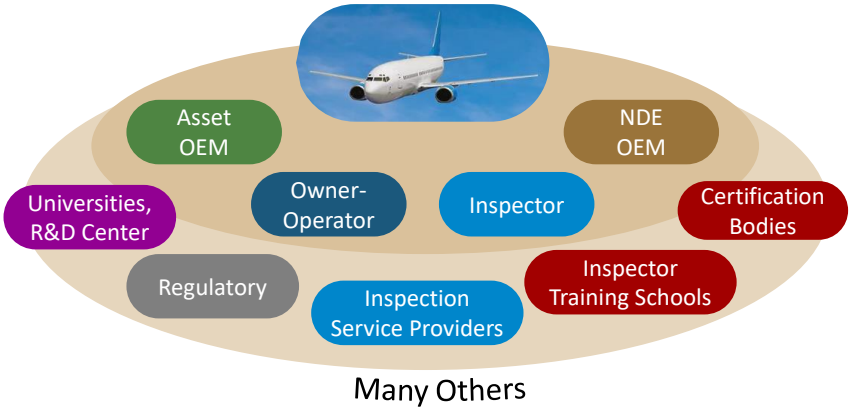
Let us understand the NDE ecosystem, stakeholders, and their value streams, and connect the use cases discussed in previous chapter.

Birds Eye view of the Ecosystem

If you focus on the asset, you can see that multiple parties contribute to its safe and economic operation, in line with the primary purpose of NDE 4.0. We use the term asset as a generic reference to a physical item – machine, vehicle, system, plant, or a piece of infrastructure that needs inspection for safety and performance assurance.

Key Stakeholders

Figure below shows the four key stakeholders in the inner circle and the supporting entities in the outer circle. Airplane Asset is just an example.



Asset Original Equipment Manufacturers (OEMs)

Asset OEMs design, manufacture, assure quality, and prescribe the in-service inspection program, along with standards and procedures for compliance. They leverage R&D out of universities and other research establishments to continuously improve their assets.

The Asset OEMs including the supply chain have the primary responsibility of delivering a product or a system that is safe to operate, affordable over the life span, and requires minimum maintenance. They essentially compete on product performance, cost, and customer experience. To accomplish this, almost every asset is adopting IIoT, from something as small as an electric switch controlling the light bulb to aerospace defense, and home appliances in between.

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4. Technology Suite of the Fourth Revolution

THERE HAS NEVER BEEN A TIME OF
*GREATER **PROMISE** OR GREATER **PERIL**.*
— KLAUS SCHWAB, CHAIRMAN WEF IN 2016

{ From Johannes heart } My main interest has always been technology, and that too at the bleeding-edge. It started when I was a kid taking apart my mom's vacuum cleaner or conjecturing in the night how an electronic calculator might work. This curiosity continued during school and led me to study physics for my graduate work. In the beginning it was mainly semiconductor physics, and for a long time, I wanted to specialize in this field. However, one day I came across quantum computers, and I was hooked. I joined a research team working on proving the entanglement of a photon and an atom – one of the fundamental research problems for quantum computing. It was a thrilling experience to play around on a table filled with lasers, mirrors, optical elements and more. Luckily, I did not hurt myself with my enthusiasm which was always in high gear.

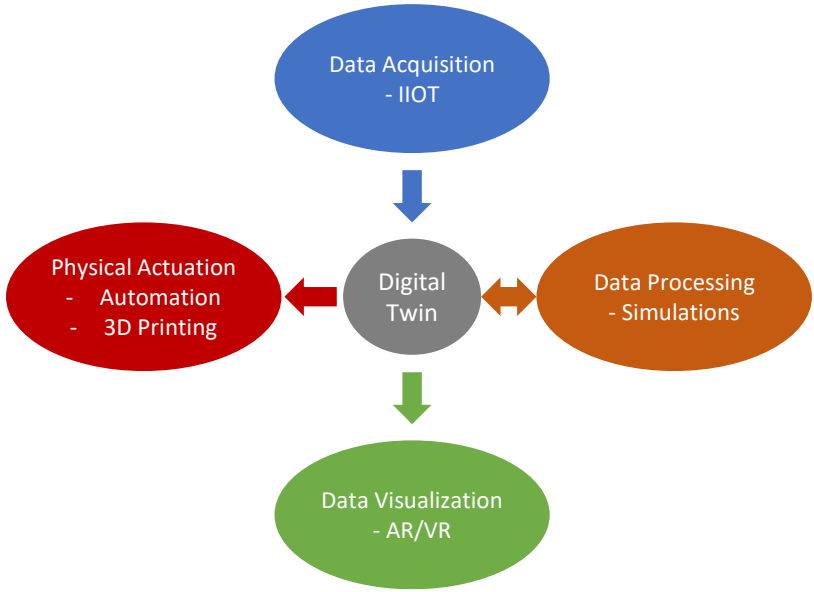
During this time, it became obvious to me that I was fascinated by pushing applications to the next level. This was my 'aha' moment, and I moved into NDE – cutting edge technologies, driven by physics, with a direct relation to applications. For years I enjoyed learning and dabbling in induction thermography, automated ultrasonics, Synthetic Aperture Focusing Technique (SAFT), and automated data evaluation (including statistical). This helped build the foundation of my passion today – the NDE 4.0. Next few chapters will show how working on NDE 4.0 is kind of a dream come true for me.

Let us start with technology suite of the fourth revolution that we are familiar with as consumers, and then explore how this addresses the use cases for various stakeholders in the ecosystem.

Technology Landscape

Every thought leader has their favorite top 5 digital technologies as a part of Industry 4.0. Which one is more important depends upon the application. Based on diverse requirements of NDE domain, all the prominent technologies will be discussed briefly in this chapter, because they are important to at least some of the use cases discussed in chapter 2. In the next few chapters, we will go deeper into digital technology portfolio that makes digital transformation possible, forming the basis of cyber-physical value creation for the ecosystem, discussed in chapter 7.

The landscape of technologies discussed is graphically shown below[22]. Industrial Internet of Things (IIoT) and Digital twin are at the core. They connect, manage, import and export data across various technologies and applications through data acquisition, managing, processing, visualization, and physical action.



[22] This list is ever evolving. Please check with authors for an update.

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5. Informatization of NDE

*THE PANDEMIC **ACCELERATED***
THE WORLD'S DIGITAL TRANSFORMATION.
— NAOMI XU ELEGANT, FORTUNE. DEC 03, 2020

{ From Johannes past } In summer of 2016, I was entrusted with organizing a virtual in-company NDE conference called "NDE Council 2.0". It was designed to be four hours/day for four days, with participants from 15 locations in four continents and seven different time zones (from Asia to USA). At that time, the teleconference tools were not that mature. Luckily, so-called 'collaboration rooms' equipped with state-of-the-art audio-visual equipment were available at all locations. But those rooms needed to be booked, sometimes almost a year in advance. Moreover, local hosts were needed at every location in addition to a technical support team. This was digitization of a conference. As digitization is the core of the third revolution the name "NDE Council 3.0" would have been more appropriate, in hindsight.

But now it has become natural for everybody to have video meetings from anywhere in the house, or even on mobile devices while in motion. A fall 2020 meeting with the ICNDT group on NDE 4.0 with over 20 participants from 15 countries using regular computers provided a better user experience than the conference mentioned above. It just took a couple of mouse clicks to plan the meeting and a couple of mouse clicks to dial in. And there is even more today: you can share your computer screen, run chat on the side, use whiteboard and sketch ideas, and save the entire proceedings on the cloud. All this with almost no need for technical support and at costs affordable for everybody. Soon, this experience will be combined with virtual or augmented reality platforms.

So, what changed in those 5 years: commercial suppliers which not only provide a digital communication platform but also the tools to support our digital process for planning, booking, and execution. The change from digitization to digitalization of conference calls.

However, there is still one major issue. There are several commercial platforms and all of them are not compatible with each other. We cannot call from Skype into Zoom the way we are able to call from any phone to any other phone (iPhone, Android, landline, …). Different organizations have different preferences amongst numerous available choices. Each one uses a certain communication platform. While some of them allow their employees to use any platform, others restrict use to certain approved modes. Sometimes, computers refuse to cooperate, and we hear things like '*technology is great when it works*'. Which means, there is another level of consumer experience that is possible, perhaps through digital transformation.

Can we have a conference where everyone is free to pick a tool of their choice (Skype, Zoom, Teams, or WebEx) and dial into the same conversation? This requires that the system providers put the customer first and change from proprietary systems to open interfaces. Such a step would not only solve the issue mentioned above but would at the same time create a new ecosystem which permits all kinds of new tools for the benefit of the customer. When this happens, we will claim that conferences have been digitally transformed, and may even call the next conference as 'NDE Council 4.0'.

We must now go from digitalization to digital transformation, which requires that the system providers be open to such a possibility of an interface and interpretation. Similarly, for a viable cyber-physical NDE 4.0 system, we must go from digital NDE equipment/method of the NDE 3.0 to digital transformation of NDE 4.0. In this chapter, we will explore what is required for digital transformation of NDE – the magic that allows data to flow friction free and be available *'at will'* to extract value. We will dig deeper into the needs and means of how the topics and technologies discussed up to the moment in this book are connected.

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6. At the Core of NDE Digital Transformation

*DIGITAL IS THE MAIN REASON JUST OVER HALF OF THE COMPANIES ON THE FORTUNE 500 HAVE **DISAPPEARED** SINCE THE YEAR 2000*
— PIERRE NANTEME, CEO ACCENTURE IN 2016

{ From Johannes Past } About a decade ago, a couple of colleagues and I started a project using NDE data to enhance the models for the lifetime estimation of certain components. During this project we faced multiple challenges.

The starting situation: Automated UT inspection of all components with C-scan or A-scan recording (depending on whether indications had been detected or not). The inspection was fully digital, but the level of digitalization was limited. It allowed the display of the results and the use of cursors, but we were not able to access the raw data ourselves because of proprietary data formats. This meant that the interpretation of the results was visual/manual. The results of the inspection were documented in Microsoft Excel using a pre-defined spreadsheet, printed, signed, and scanned.

The NDE data we needed for the lifetime estimation program were all documented on the UT report. We had to hire an individual who had to get all the reports from the ERP system and retype the content of the scanned PDFs into a big spreadsheet. It took that person ONE year. I guess this was also the reason for the limited accuracy of the data we had. So, we had to hire another person to quality check all the content, for almost three months. Please ask them how much they loved their job.

In the meantime, my team and I set up a database structure to capture all the results on the reports, an HMI to visualize the data, and the tools for the statistical analysis. We also required all the inspectors to save the Excel files along with the scanned PDF and implemented a tool to import

the Excel files directly into the database. This was kind of a small digitalization step – but one which saved a lot of time and made the process clearly less error-prone.

And the result – with all the additional knowledge we gained out of the statistical analysis of the NDE data, we were able to allow a way longer lifetime than before, recovering our investment. What I can say: afterwards, nobody (besides the ones you will always have within every company) questioned any more the value of the UT inspection.

Now imagine how much easier this would have been if the data were already in a format which could just be used; if we had an automatic data processing of the results; if we had an open interface directly feeding the results into the database; an IIoT; or if we had a digital twin for the lifetime estimation, directly using the data from the IIoT, from the inspections.

The Fundamentals

To understand the digital transformation at the ecosystem level, we must first figure out the digitalization and digital transformation for each of the major stakeholders in the value stream. The vision is to have a system where data from all sources is accessible in a manner that can be used by any element to generate value for themselves as well as other parties. It may seem like a long stretch to get to such a reality, may even appear impractical, but a perspective and possibility is inspiring enough for us to discuss it here with you.

The core of this Ecosystem is the cyber-physical loop processing digitized data representing one or multiple physical properties. Some examples are financial data, design data, data from production, data from operation, data from (NDE) sensors, or data from classical NDE inspections. The accumulated data is used for some data processing, like feedback, trending, or predictive maintenance. The results are visualized to gain knowledge which can eventually be used to invoke the necessary actions for process improvements.

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7. Cyber-Physical Value Creation in NDE

THIS IS NO LONGER A BATTLE OF DEVICES,
*IT IS A **WAR OF ECOSYSTEMS***
— STEPHEN ELOP, FORMER CEO NOKIA IN 2011

{ From Johannes heart } A fine afternoon in June 2018, I also got an email from Claudia of ASNT, asking if I would be willing to work with Dr. Singh on my proposal to organize sessions on NDE 4.0 at the upcoming ASNT annual conference.

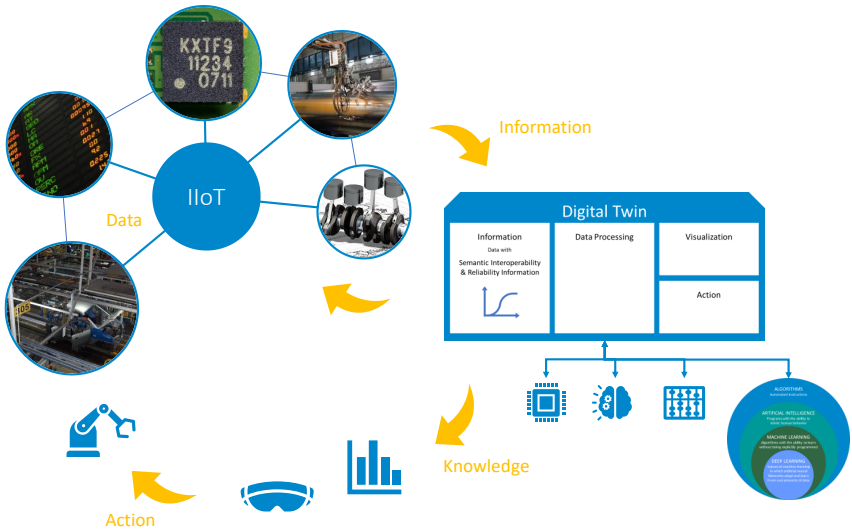
You might remember similar words from chapter one – but I am not going to repeat that story, I will talk about the long-term effects.

Already during our initial beers, it became apparent that we both had different views on all the topics of NDE 4.0, but we continued listening to each other. Luckily, we used the same semantics, and we were able to combine our ideas into something bigger. Kind of what IIoT and Semantic Interoperability can do for technical devices. We started to process the combined ideas to create additional knowledge – just like a digital twin, and we provided each other feedback widening our views – just like the cyber-physical Loops. Those feedback loops were quite tiny – just between the two of us.

The loops grew bigger with every session or panel we organized, with every presentation we were able to give, with every conference we helped organize, with every group of stakeholders we were able to interact with. This became the start of a knowledge sharing ecosystem which could achieve so much more than we could do individually – and it helped both of us to achieve more than we would ever have been able to on our own.

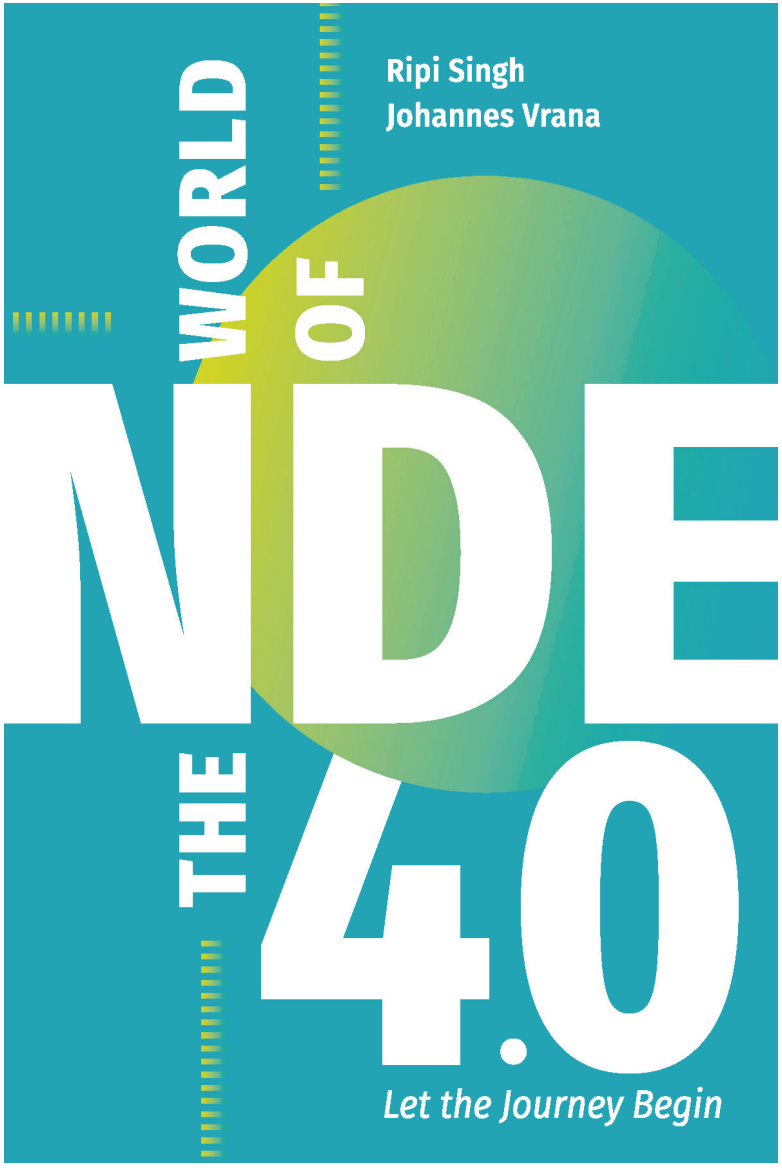
Basic Cyber-Physical Loop

The value creation in fourth revolution comes from closing the cyber-physical loop (which is also called the physical-digital-physical loop), with the IIoT and the digital twin as the core contributors or enablers. The sensors in the physical world bring digital data, which is then converted into information by semantic interoperability, combined with other pieces of information, processed by the digital twin to create knowledge, which finally leads back to actions in the physical world.



Human in the loop is a matter of technology maturity, and acceptance. We will continuously see more automation in the loop. Just like we have gone from cruise control to self-driving cars in about 30 years; we will go from human-in-the-loop to human-on-the-loop and eventually human-out-of-the-loop.

Over the life cycle of a product, there can be a number of loops providing a wide range of value to various stakeholders of the NDE 4.0 ecosystem as shown in figure below.



Now available here:

https://www.amazon.com/dp/B09DZXQ3Z1

Review by Prof Dr. A. Erhard & Dr. T. Wenzel, DGZfP

Industry 4.0 is a trend since some years of automation and digitalization of industries and embrace all singular branches which makes industry strong. To guarantee the safety of constructions and components are among others fracture mechanics and the techniques of the non-destructive Testing (NDT) essential tools. Therefore, it was necessary to adapt NDT on this trend especially the evaluation of the data outcoming from the NDT, the so-called non-destructive evaluation (NDE) or in newer days NDE 4.0.

There is clearly more behind the term NDE 4.0 than just a new trend, a new technology or further development of existing NDE processes. The term "disruptive" is much more appropriate here, because NDE 4.0 introduces a new field of application, even a new era, to non-destructive testing. NDE 4.0 opens up new applications and markets, but it also poses major challenges for the NDT community, requiring a different mindset as well as courage and leadership to successfully take this major step. This is true for equipment manufacturers, service providers and researchers, but also for end users who have to embrace the new solutions and opportunities.

This book provides a deep insight into the opportunities and possibilities created by NDE 4.0. It shows the added values for the users, which enables them to continuously improve their products and processes. NDE 4.0 provides information that, in the context of data from other sensors, enables a more detailed analysis of root causes than was previously possible.

The book NDE 4.0 sheds light on what is necessary to adequately meet the many challenges from every perspective and thus provides nourishment for every reader who wants to approach the topic. The spectrum of topics covered ranges from technology to organization, economic aspects to sociological and legal issues. The comparison made in the book to a journey that one embarks on as soon as one follows the path of NDE 4.0 becomes increasingly clear from chapter to chapter. This makes the book an indispensable travel companion for anyone who wants to take in all the attractions of the NDE 4.0 journey.

August 23, 2021

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— Prof. Dr. Anton Erhard and Dr. Thomas Wenzel, DGZfP

This book provides invaluable insights into the value and use of NDE 4.0 for all — from technicians to corporate leaders!
— Dr. Claudia Kropas-Hughes, Fellow ASNT, Fellow ASME

This is a very well written book and an excellent source for NDE 4.0 from two of the leaders in the field!
— Prof. Dr. Christian Große, TU Munich

This is a captivating narrative that reveals the complex concepts of NDE 4.0, even to a layperson, by provoking our thinking process, in every section, through this easy reading book.
— Prof. Krishnan Balasubramaniam, Head CNDE IIT Madras

Inspiring Next Inspection Ecosystem

Dr. Ripi Singh (USA) and Dr. Johannes Vrana (Germany) have been leading applied research in NDE 4.0; global community efforts with ICNDT, EFNDT, ASNT, and DGZfP; sharing knowledge through editorial work with Journal special issues, Handbook of NDE 4.0, keynote lectures, special sessions, panel discussions at international conferences, and a stable YouTube channel. They aspire to build a purposeful NDE 4.0 ecosystem for stakeholder safety and economic value. You are invited to join the movement.