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NDE 4.0

OBJECTIVE - This Journal of Non Destructive Tesing & Evaluation (JNDE) is published quarterly by the Indian Society for Non Destructive Testing (ISNT) for promoting NDT Science & Technology. The objective of this Journal is to provide a forum for dissemination of knowledge in NDE & related fields. Papers will be accepted on the basis of their contribution to the growth of NDE Science & Technology.

PUBLISHED BY: Mr. Bikash Ghose - Managing Editor, JNDE

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LETTERS

PRESIDENT TALK

DIWAKAR JOSHI

Dear Friends

Greetings!

September 2023 issue of JNDE was on "NDE of Civil Infrastructure" which is a very important topic in the current scenario. It was well received by the readers. The current issue is on NDE 4.0

Coincidently, our National seminar is having the theme "Transformative NDE: Unleashing the Power of Advanced Technologies". The focus will be on NDE 4.0 and topics such as artificial intelligence, robotics, and advanced sensors, which have the potential to revolutionize NDE practices and enable more efficient and effective inspection processes. I am sure you all will be eager to attend the same.

You will be happy to note that the second program of PFMB on the subject of '2D & 3D Industrial Radiological Imaging and their applications was completed at IIT Madras on 25th & 26th September 2023 with excellent participation. You can expect many more programs from PFMB in the near future.

NCB is making efforts to connect to the regulatory bodies and Industries to promote our certification schemes. I sincerely appeal all members to ensure that ICN scheme is promoted at all places. The final authorization of the chapters and training centers is in progress.

There are a lot of activities happening in the chapters including webinars, training programs and workshops, which is a good sign. Many chapters have started releasing E-Bulletins regularly.

The International conference on NDE 4.0 will be happening in India in March 2025 and the preparatory work is already started.

I thank all authors, the editorial board, advertisers, and the whole team for releasing this issue in time. I am sure the readers will enjoy this issue.

Greetings for the forthcoming festive season and eager to see you all at Pune in Dec 2023 for NDE 2023.

Diwakar D. Joshi
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MANAGING EDITOR TALK

BIKASH GHOSE

Greetings from Indian Society for Non-destructive Testing.

We are happy to bring out another special issue of JNDE on NDE 4.0 within year. This signifies the importance ISNT places for NDE 4.0. This issue is again spearheaded by Dr. Shyamsunder Mandayam.

This issue is to introduce our readers and the NDE community about the exciting topic of NDE 4.0 which is emerging and growing at an extremely fast pace around the world. You are all aware that the ongoing fourth industrial revolution popularly called Industry 4.0 is based on digitisation, digitalization and digital transformation combined with several other elements of Big data, Analytics, Robotics, Internet-of-Things, Artificial Intelligence, Digital Twins and many others which is supported through NDE 4.0. Six interesting papers in this issue covering different aspects of NDE 4.0 will provide you greater insights on the topic. These original research articles to JNDE can be assessed at JNDE's online portal https://jnde.isnt.in.

We take pride to inform that the 3rd International Conference on NDE 4.0 will be hosted by ISNT in Bengaluru during March 2025 and will be a big boost for this emerging, globally relevant topic.

My heartfelt thanks to Dr. Shyamsunder Mandayam for agreeing to be the Guest Editor for this issue. Sincere thanks to all the advertisers and contributors of this issue who helped release the issue on time.

The chapter activities section summarizes the activities conducted by various ISNT chapters in the last three months. ISNT's 33rd Annual Conference 'NDE 2023' to be held on 7-9 Dec 2023 at The Hotel Orchid in Pune is waiting for your cordial presence.

Bikash Ghose
Managing Editor, JNDE
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GUEST EDITORIAL FOR JNDE SPECIAL ISSUE ON NDE 4.0

DR. SHYAMSUNDER MANDAYAM

ISNT's Journal of NDE's Special issue on NDE 4.0 is now in your hands. This is the second such Special issue on this topic, the previous one having been released in December 2022. NDE 4.0 is a topic garnering great interest and curiosity with an exponential growth globally. This is very evident in the number of books and journals published as well as the dedicated sessions in conferences and seminars on this important topic.

This Special issue continues the journey from the previous issue with newer and more exciting topics for the NDE community at large. NDE 4.0 is a key enabler for Industry 4.0 and will lead to an improved productivity, efficiency, reliability and safety of components / structures/assets during manufacturing and while in-service. Adoption of NDE 4.0 by the industry is a long and fruitful journey which has started but needs to be strongly supported, encouraged and motivated in all segments of academia, R&D and Industry. We have very interesting papers for you in this issue covering several aspects of NDE 4.0 and will provide a treasure house of information to our readers.

This issue is also a pre-cursor to the very exciting event - the **3rd International Conference and Exhibition on NDE 4.0** which will be jointly hosted by ISNT and ICNDT in India during March 2025 and will attract the best national and international experts and practitioners on one platform to share, discuss, debate and recommend the current status, success stories and the way forward for this emerging, globally relevant topic.

We hope you enjoy browsing and reading through this content packed with the papers along with our other regular features. Please share your feedback or suggestions if any at me.jnde@isnt.in

Dr. Shyamsunder Mandayam
Guest Editor, JNDE Special Issue on NDE 4.0
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Ahmedabad

Other Activities :

30/10/2023 -ISNT-PDEU Student Chapter activity on Training on Sand Casting

Bengaluru

Other Activities :

a) EC Meeting conducted on 25th Sept 2023. 12 EC members were attended.

b) EC Members are working to take IS 13805 Accreditation to the Bengaluru chapter in four methods, i.e., UT, RTFI, PT and MT

c) Planning to conduct one more EC meeting on Oct -2023

d) Planning to conduct second RTFI Program at Reliance in the month of Dec-2023

Chapter Chairman, Hon Gen Secretary and Dr. Shyamsunder are involving to finalise the new Event management company and Venue for IC NDE 4.0 -2025

Chennai

Course & Exam :

- Ultrasonic Testing Level-II course and examination was held on 22nd August 2023 to 2nd September 2023. Number of candidates attended the course was 9 and examination was 11.
- Radiographic Testing Level-II course and examination was held on 4th October 2023 to 14th October 2023. Number of candidates attended the course and examination was 13.
- We are planning to conduct Surface NDT MT & PT Level-II course and examination from 16th November 2023 to 25th November 2023.

Other Activities:

- EC Meeting was held on 27th August 2023
- EC Meeting was held on 8th October 2023
- 10th E-Newsletter – Sound Bytes were released on 10th September 2023

SOUND BYTES
Decibel 23
Frequency 3
September 2023 issue
Email ID: soundbytesisnt@gmail.com
Official Newsletter of ISNT Chennai Chapter

Dear Readers,

Greetings to you all.

Few days back when I was with my friend happened to chat with his grand-daughter. During the course of my enquiries about her studies, she replied that it is no problem as she is relying heavily on chat GPT for her homework. I was wonderstruck and it occurred to me why we cannot explore the possibilities of putting it to use for our day to day inspection activities. While I was vacillating whether to venture into the adventure or not, today morning, my friend Sri.V.Pari sent me a whatsApp message which I had used it as the emblem for this column. Why can't we follow a bright student, hence this article.

Intelligence: According to oxford dictionary means, the ability to learn and think to a logical way about things; the ability to do this well.

From the above we can deduce that the intelligence is conclusion of how to surmount a challenge being faced with the application of one's academic knowledge and practical experience gained. This process varies from period to period of one's life and the data accumulated in his life time. So it boils down to data collected regarding the challenge.

Artificial intelligence: According to oxford dictionary means "An area of study concerned with making computers copy intelligent human behavior.

With the advent of computers as the processors became more and more powerful, plenty of activities considered as mundane by human beings, have been shifted to the computers for more accuracy and speed. This means that voluminous data have been transferred and stored in their memory and the computers are taught to respond to a question. The more precise a question the more precise will be the answer. The answer is heavily dependent on the question and how the computer understands it so much so the question is the interface between computer and the human. Therefore the questioning technique is the axis around which the answer is developed. That is why ChatGPT cautions in using their solution.

AI will soon advance into every aspect of our day to day life and let us prepare ourselves to interface it in our dealings with our work routine. Let us focus on sharpening our communication skills with the computer. In future, " Communication with Computers " will be included in the skill development programme of college educational syllabus.

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We have received certificate for Authorisation by Training Management Board of ISNT to conduct Training Programme in accordance with IS 13805 – ET, LT, MT, PT, RT, UT and VT Level-II

Hyderabad

Other Activities:

- 4th Sep'2023: ISNT Hyderabad Chapter's Executive Committee (EC) Meeting was held on 4th Sep'2023 at GURUKUL, NFC, Hyderabad. Discussions were held regarding conducting NDT courses as per immediate requirement and also ATC status of ISNT Hyderabad Chapter. All EC members unanimously felt that conducting NDT courses should not be halted in the process of authorization to ISNT Hyderabad chapter by TMB/ISNT Head Office.

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Dual Mode
High Temp.Application

Aerosol & Bulk Packings

High Quality Products

Meet Requirements of all International Specifications

Distributors For Local Requirements at all Industrial Locations

Flaw Guide
NDT Products

Fluorescent Powders For MPI

Water & Oil Suspended Carrier Oil

Packings
1 / 5 / 20 Kgs

Flaw Guide
NDT Products

White Contrast
Black Ink
Fluorescent Ink
For MPI

Ready to Use
Aerosol Sprays
&
Powders in Bulk

- 22nd Sep'2023: ISNT, Hyderabad Chapter and Nuclear Fuel Complex have jointly organized a One day Theme-Meet on "Eddy Current Testing in Tube Manufacturing and In-Service Inspection" on 22nd Sep, 2023, at Gurukul, NFC Training School, Nuclear Fuel Complex, Hyderabad.
- Excellent response was received from various organizations and industries for participation in the theme-meet. Around 60 participants from various organizations attended the theme-meet. Speakers from NPCIL, BARC, IGCAR, NFC, TECHNOFOUR and EDDYFI TECHNLOGIES have delivered talks on various topics covering ECT applications in manufacturing process, Heat Exchanger Tubing Inspection, and In-service Inspection. Equipment manufacturers have shared the latest advances in ECT Technologies. Main objective of the theme-meet was full filled in bringing experts, working professionals, Equipment manufacturers on to a single platform for knowledge-sharing.

Speakers from various organizations viz. NFC, EDDYFI TECHNOLOGIES, TECHNOUFOUR, BARC, IGCAR, NPCIL along with Dr. Komal Kapoor, Chairman, ISNT Hyderabad Chapter during Inauguration of theme-meet.

- Inauguration of theme-meet by Dr. Komal Kapoor, Chairman & Chief Executive, NFC and Chairman, ISNT Hyderabad Chapter; EC Members of ISNT Hyderabad Chapter are also present.

Participants of Theme-Meet on" Eddy Current Testing in Tube Manufacturing and In-Service Inspection" from various organizations

Kolkata

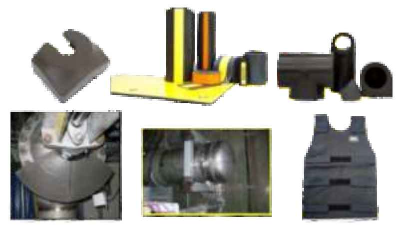
Other Activities:

- Condolence meeting of Pr Madhusan Bhattacharya, Ex. Chairman ISNT, Kolkata was conducted.

EXERTUS CIRCA 80

Se-75 Close Proximity Projector

SILFLEX SHIELDING MATERIAL



EXERTUS DUAL 120

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IRIDIUM 192 | COBALT 60 | SELENIUM 75

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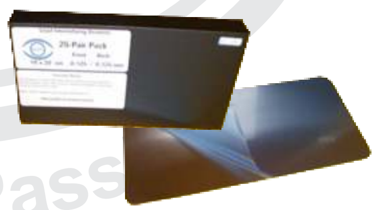
Iridium-192/Se-75 Projector

SPEC-300

Cobalt-60 Projector

LASER INDUSTRIAL X-RAY FILM & CHEMICAL

RADAC LEAD INTENSIFYING SCREEN



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Mumbai

Other Activities:

NDTi Symposium & AGM 2023 conducted 29th Sep 2023. 190 Members Attend the function.

Sriharikota

Technical Talk:

A Technical Talk by Dr. M.T. Shyamsunder on the topic : "Emergers, Enablers, Enhancers (E3) for Inspection Technologies.

Venue: SDSC SHAR, Sriharikota

Date: 08-09-2023

Other Activities:

On 09-09-2023 & 10-09-2023, NGC, NCB, TMB meetings conducted at SDSC SHAR, Sriharikota

Trivandrum

Technical Talk:

- Two Day Workshop on 2D/3D Industrial Radiological Imaging and their Applications conducted on August- 3rd and 4th, 2023 at LPSC, Valiamala, Thiruvananthapuram.

The program was jointly organised by PFMB and ISNT Thiruvananthapuram Chapter. Around 120 participants attended the program

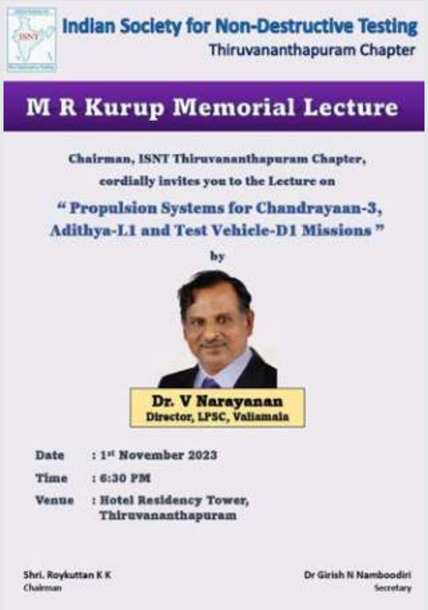
- M R Kurup Memorial Lecture on "Propulsion Systems for Chandrayaan-3, Adithya-L1 and Test Vehicle-D1 Missions" is conducted on November 1st, 2023 at Hotel Residency Tower Trivandrum.

Other Activities :

Annual General Body Meeting 2022-23 was conducted by the Chapter on 08.09.2023. New EC was elected in the meeting. More than 100 members attended the function.

Industrial Visit has been arranged to Cochin Shipyard on 18th November, 2023. More than 60 members had registered and visited.

New Executive Members of ISNT Thiruvananthapuram Chapter



Trichy

Course and Examination :

- 26.10.2023 – 06.11.2023 BARC RT Level – 1

Technical Talk

1. 05-09-2023 - Industrial Hazards and Its Mitigation Measures.
2. 19-09-2023 - Stay Safe Online: Best Practices.
3. 26 –09 -2023 – Opportunities for Engineers in modern India.
4. 06-10-2023 - Resilient urban economies. Cities as drivers of growth and recovery

Vadodara

Other Activities :

Date: 21-August-23 : Second Executive Committee Meeting of ISNT Vadodara Chapter had on 21-August-2023 at ISNT Vadodara Chapter office.

Date: 06-September-2023 : Special online meeting had with ISNT HO Team for resolving issue for auditing GST Data for NDE-2022 vide GST Number of ISNT Vadodara Chapter.

Attendees : From: ISNT Vadodara Chapter:

Shri. R. Venkatasubramanian (Hon. Chairman – ISNT Vadodara Chapter), Shri Kashyap Bhatt (Hon. Secretary ISNT Vadodara Chapter), Shri Krutik Shah (Hon. Treasurer) ISNT Vadodara Chapter.

From ISNT Head Office :

Shri K.A. Nerurkar (Hon. Treasurer ISNT HO), Shri K. Venkateswarlu (ISNT HO), Shri Harish Chug (Auditor ISNT HO), Shri V. Pari (Member Secretary – QUNEST Fdn.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SPECTRO-UV
Chemetall
L.G. INSPECTION SERVICES
LGI
NDT Inspection (MT, PT & UT)
Eddy Current Testing
Authorised Distributors
MR CHEMIE NDT-materials
ARORA NDT Products & Accessories

TRAINING MANAGEMENT BOARD

Training Management Board (TMB) – ISNT

The Training Management Board (TMB) was officially formed by ISNT in February 2022 to act as a nodal agency to address all NDT training related activities (which lead to formal certification as Level 1, 2 or 3 personnel under IS 13805 and ICN schemes of ISNT). Over the period of nearly 23 months since its formation, TMB has made good progress on several fronts by creating multiple Task Forces focussing on different tasks including creation of harmonized timetables, Training material for course instructors, Course notes for trainees, Question Bank / Mockup exams, Train-the-Trainers programme. The other major activity which was the focus of TMB was to establish a robust process with appropriate guidelines, mechanisms and teams to establish Authorized Training Centres (ATC) of ISNT across the country (and later abroad) who can conduct effective and harmonized training courses for both the schemes in all the NDT methods at all Levels of certification. This was achieved by the dedicated Task Force set up for the purpose under the leadership of "Controller of Authorization". The "Call for Applications" from interested entities for Full Authorization as an ATC valid for 5 years through an audit and assessment process was announced and we welcome all to take advantage of the same.

As of November 2023, we have 2 ATC's authorized for both IS 13805 and ICN schemes and 1 ATC for IS 13805 only. Details of these ATCs can be found at https://isnt.in/about-tmb/

Through TMB's focused efforts, it envisages a standardized and harmonized training system to be in place in the near future which ensures a world class NDT training ecosystem in all aspects.

We also welcome volunteers to join and contribute to TMB activities in whatever way they can to help accelerate the fulfilment of our objectives.

To learn more about TMB and its activities please visit https://isnt.in/

For any queries related to TMB, please send an email to tmb@isnt.in

PROGRAM FORMULATION AND MANAGEMENT BOARD (PFMB)

I wish to inform you that the Program Formulation and Management Board of ISNT (PFMB) has been constituted with Shri V. Manoharan as the Chairman, Dr. Deepesh Vimalan as Hon. Secretary and 14 technology/industry experts as members of the board.

PFMB has formed 4 technology groups –Radiological Imaging, Electromagnetic NDE, Thermal Imaging, and Acoustic NDE and Chairman for each working group were identified.

Office Bearers

Shri V. Manoharan, Chairman

Shri Deepesh Vimalan, Hon. Secretary

Members :

Dr. S. Thirunavukkarasu
Mr. A.K. Das
Dr. Phani Suryakiran
Mr. Bhausaheb Pangare
Dr. Arumugam. M
Prof. Prabhu Rajagopal
Dr. Menaka
Prof. Kavitha Arunachalam
Mr. P. Vijayaraghavan
Prof. Ravibabu
Mr. Komma Reddy Vamshi
Dr. Debasish Mishra
Mr. Umankanthan Anand
Dr. Ramadas Chennamsetti

Ex-Officio Members

Mr. Diwakar D. Joshi, President -ISNT
Mr. Bikash Ghose, Hon. Gen. Secretary -ISNT
Mr. Kalesh Nerurkar, Hon. Treasurer ISNT

Invitees

Dr. Paritosh Nanekar, Chairman-NCB
Dr. M.T. Shyamsunder, Chairman -TMB

Objectives

The main Objectives of PFMB are as follows:

- To conceptualize, formulate and organise various non-certification programs such as Webinars, Workshops, Conferences, Seminars etc. to create platform for constant interaction with ISNT members, meet the requirement of industry, academia and research community.
- To interact with other international NDT societies, National technical societies to formulate and organise joint programs.

Scope

- To plan and organise two annual conferences of maximum 2 days' duration (other than NDE) and execute through an organizing committee nominated by PFMB
- To conceptualize, formulate and execute programs such as Webinars, Workshops, Conferences, Seminars etc. of relevance to the NDT community to be organised by ISNT throughout the year across the country.
- To publicize the proposed program
- Develop and implement mechanism for executing the programs along with ISNT Chapters or independently (only if no chapter is interested).
- Create various topical working groups within PFMB and formulate programs as stated above for meeting specific requirement.
- To connect with various industries / institutes and formulate program to meet the specific needs
- Interact with international NDT societies (ISNT partner societies with MOUs) for conducting joint programs, pre-dominantly Webinars
- Interact with national technical societies for conducting joint programs
- Establishing a model for sustained revenue generation for continued operations and growth of PFMB

Program Formulation and Management Board (PFMB) with the technical working groups are progressing well under the scope of PFMB.

First Programme of PFMB :
Topic : "2D/3D Industrial Radiological Imaging and it's Applications"

The first ever PFMB workshop was conducted successfully by ISNT Thiruvananthapuram Chapter on August 4th and 5th, 2023, on the theme, "2D/3D Industrial Radiological Imaging and it's Applications. This program had a very good response with a total of 119 Participants for this workshop. Dr. Narayanan V, Director, LPSC inaugurated the program and welcomed all participants to LPSC. He mentioned the important role played by NDE in aerospace sector and its relevance. Shri M.S. Suresh, Associate Director/LPSC, Dr. Arumugam. M, Dy. Director/LPSC and the Program Coordinator, Shri V. Manoharan, Chairman, PFMB, Dr. Mohan Kumar. L, Chairman, ISNT Thiruvananthapuram Chapter, and Shri Roykuttan K.K, were the organising Committee Chairman addressed the gathering.

Second Programme of PFMB :
Topic : "2D/3D Industrial Radiological Imaging and it's Applications".

The second workshop on the same theme, "2D/3D Industrial Radiological Imaging and it's Applications", was also conducted on 25th and 26th of September at IIT, Chennai jointly organised by PFMB-ISNT and QUNEST Fdn. in association with CNDE, IIT. This program was also well received with good response with a total of 85 Participants.

Shri H. Shankar, Director Technical, CPCL, Chennai was the Chief Guest for workshop. Shri S. Ramakrishna was the Programme Director and Shri V. Manoharan, Chairman-PFMB.

The workshop was well represented by various industrial sectors and was a grand success.

Upcoming programme :

During NDE 2023 (7-9, Dec 2023), a special session : IGNITE (Carrier in NDE) specifically for the student community will be conducted as part of NDE.

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- VJ Imaging Technologies Pvt Ltd

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Guideline for the Development of an NDE 4.0 Roadmap

Ripi Singh[1], Ramon Salvador Fernandez[2], and Johannes Vrana[3,4]

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Abstract

‘*What you don't know can't hurt you*’ does NOT apply to Digital Transformation, as it is changing the value proposition from ‘competitive advantage’ to a ‘must do initiative’. NDE has seen revolutions somewhat parallel to industry. The current trends in cyber-physical technologies offer new possibilities wherein the inspectors can see the anomaly on a digital twin before they can see it on the conventional equipment, by fusing data from multiple sources and leveraging history captured in digital threads. To convert such a possibility into reality, organizations need a roadmap, particularly when the ecosystem is still evolving. Roadmaps are instrumental for guiding and thrusting sociocultural, economic, technological, and even political changes around the world.

This paper provides a guideline to the various stakeholders of the NDE ecosystem to develop a roadmap for NDE 4.0. Meaning this paper provides the necessary support regarding HOW to realize the value propositions of NDE 4.0, which have been developed in earlier publications [1,2,3,4,5].

Keywords *: Industry 4.0, Digitalization, Inspection reliability, Digital Transformation, Roadmap, Value Creation, Innovation*.

1 Introduction: The Genesis of NDE 4.0

1.1 Historical Evolution

Historians identify three industrial revolutions since the second half of the XVIII century: mechanization (steam power), technical (electric power and mass production), and digital (computing and microelectronics). The world of NDE has seen a parallel: first - tools to sharpen human senses, second - wave applications to view inside the components, and third - 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 with the addition of information transparency, technical assistance, machine intelligence, decentralized decisions, and much more. The line between non-destructive evaluation (NDE) and the fourth industrial revolution is getting blurred since both are sensory data-driven domains. This multidisciplinary approach has led to the emergence of a new capability for non-destructive evaluation, now termed as NDE 4.0. The NDT community is coming together once again to define the purpose, chart the route, re-align the organizations, and address the adoption of emerging technologies.

NDE 4.0 is defined as a Cyber-physical Non-Destructive Evaluation; arising out of a confluence of industry 4.0 technologies and traditional NDE physical methods, to enhance inspection performance, decision making for safety and quality assurance, as well as provide relevant data to improve the design, production, and maintenance [1,2]. The fourth revolution integrates the digital tools (from third) and physical methods of interrogating materials (from second) in a closed-loop manner reducing human intervention and enhancing inspection performance. Within the context of the physical-digital-physical loop of NDE 4.0 [3,4,5]; digital technologies and physical methods may continue to evolve independently, interdependently, or concurrently. The real value is in the concurrent design of an inspection system through the application of Digital Twins and

Digital Threads [3,4]. This provides the ability to capture and leverage data right from materials and manufacturing processes to usage and in-service maintenance, creating value across the ecosystem [3].

Readers new to this subject are highly encouraged to use [1,3,4] as companion documents that provide the technical context in more than sufficient detail.

1.1 The ineluctable necessity of guidance

In [1] the digital technologies relevant to NDE were covered in a design thinking approach. In [3] the value proposition of NDE 4.0 for various stakeholders in the eco-system was discussed and in [4] the core technologies to enable NDE 4.0, like Industrial Internet of Things, Digital Twin, and Cyber-Physical Loops. Those publications covered the WHY and WHAT for NDE 4.0. An extensive description in the context of NDE has been published in the book "The World of NDE 4.0" [6]. The state-of-the-art in NDE 4.0 has recently been captured in the Handbook of NDE 4.0 [7]. All these publications create a nice vision of the future of NDE and a good indication of seemingly complex technologies. What is missing from the published literature on the topic is HOW to plan it out that makes business sense.

There is an extensive suite of digital technologies [1], and their impact is reasonably well understood as standalone pieces. However, their combination not only adds complexity, potentializing value generation but requires a deeper understanding. An increased bi-directional permeability of NDE and digital competencies in the workplace generating competency gaps that are real and have a profound impact, particularly at the union of digital and NDE skills. The two communities speak different languages, exhibit diverse demographics, learn differently, and more importantly have different viewpoints on technology adoption. A serious question today is - should you train an NDE expert on digital skills or an IT expert on NDE skills, while we wait for NDE schools to develop individuals on multidisciplinary competencies. The changing role of inspectors adds another level of complexity and resistance to the adoption of what can be hugely beneficial for everyone. An unsatisfied demand of highly specialized NDE technicians in specific niches runs parallel with the irruption and democratization of NDE technologies contained in digital direct-to-consumer products, such as IR sensors attached to mobile phones.

NDE, as a professional discipline, serves almost every industrial sector with infrastructure, and some of them are heavily regulated. Regulations inhibit transformation, provide friction to change, and need to be addressed if we were to leverage the digitalization of inspection processes. Quite often, the role of NDE is perceived to be a necessary evil and hindrance to operations. Thus, it gets relatively less attention during business investment decisions. The change agents, who can see the value in digitalization of NDE need help to overcome inertia and internal friction. They need tools to manage limited resources to unleash unlimited potential because NDE is transitioning from a niche role as a quality control support instrument to an invaluable knowledge-generating process able of creating significant value through substantial improvements in business sustainability, quality, and safety, that is why NDE 4.0 roadmaps are required to provide purpose and guidance for transforming the role of NDE in several regions of the world and industries.

The enormous leap in technology application and value realization tied to the fourth industrial revolution or digital transformation [8] can also be termed as massive transformation purpose (MTP). It is easier said than done. It requires leadership commitment, serious planning, and investment over a sustained period of time. It requires a roadmap that defines the HOW, starting with actions now and here. An explicit need for such a guidance has also been highlight by the recently formed Special Interest Group on NDE 4.0 (SIG-NDE-4.0) within International Committee for NDT (ICNDT). This paper provides a guideline to develop an executable roadmap for NDE 4.0.

2 Kickoff

2.1 Leadership Commitment

All transformation efforts begin with the identification of a leadership team and it sustains as long as the leadership stays committed. To kick off an NDE 4.0 initiative, the organization must first identify a leadership team, that includes top executives and external experts, with oversight from Advisory Boards. There should be one champion to guide the roadmap development and execution. This champion needs to be passionate about safety and quality through inspections and supported by other leadership level team members including the finance, IT, and business development. The leadership team should quickly establish the following high-level items for the roadmap initiative.

2.2 Purpose

The leadership team should define and communicate the Massive Transformative Purpose (MTP) along with priorities for NDE 4.0. This MTP should provide a clear and aspirational point of reference to the intended roadmap initiative. This could be in form of enhanced safety, quality, reliability, performance, talent, technology, economic value, or sustainability through digital-physical integration. The NDE 4.0 purpose must align with the organization's primary business strategy. Several use cases were captured in [1,4]. Sustainable development and sustainability should be a consideration or constraint at the least.

This Purpose definition, in the form of an MTP, should consider the following attributes:

a) Grounded in sound engineering, science, and management principles
b) Being massive and aspirational in its scope
c) Must demonstrate a clear "why"
d) Clearly focused on large-scale transformations
e) Unique to the organization(s) or communities involved
f) Wildly aspirational to ignite the passion and unify the action.
g) Aimed at achieving profound transformations
h) Forward-looking

2.3 Eco-system Context

The context of NDE is anchored around the asset being evaluated, be it a single part under inspection in a manufacturing line or an infrastructure undergoing in-service maintenance. Any and every entity that comes in direct or indirect contact with an asset to assure its safety and quality can be thought of as belonging to the NDE eco-system. A typical representation is depicted in figure 1. Primary or core stakeholders (inner blue circle) have a substantial influence over the roadmap initiative. Support stakeholders (outer green circle) may or may not influence the roadmap initiative. Leadership needs to define the context for their organization. This figure has evolved compared to [3], in a spirit of continuous learning and improvement.

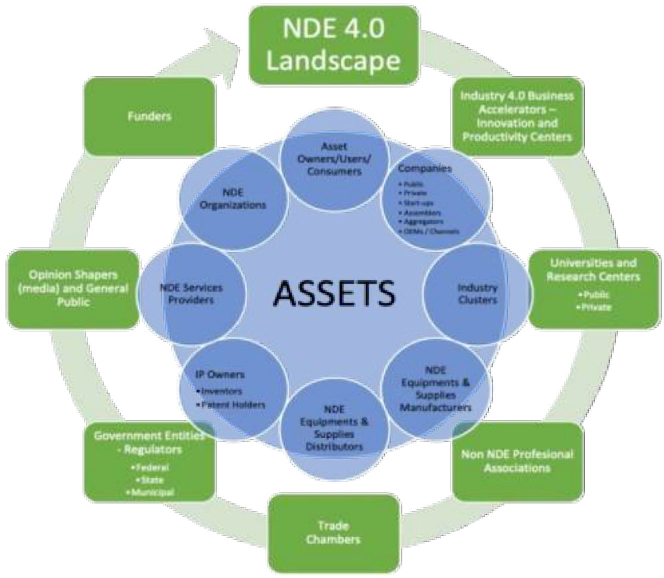


Figure 1: *NDE Eco-system with 'asset to be inspected' at the center.*

2.4 Vision

Once the leadership team has captured the context, it must establish a vision of a digitalized inspection system or a digitally transformed quality/safety assurance solution with a time horizon to accomplish the purpose. A good vision has many of the following characteristics:

a) **Graphic and imaginable**: Paints an accessible picture of the future, the organization strives for.
b) **Compelling and inspiring**: Moves people to act, igniting desire and personal connection.
c) **Focused**: Provide guidance in making decisions and allocating resources.
d) **Feasible and realistic**: Within the realm of resources and timeline, without undue stress.
e) **Desirable**: Indicates why the chosen path makes sense for the long-term interests of stakeholders.
f) **Addresses** triple bottom line growth – profit, people, and planet.
g) **Simple**: Brief, clear, easy to communicate and understand.

These characteristics also flow down to the roadmap.

2.5 Policy

The leadership team should develop and implement a digital transformation policy if it does not already exist. The policy should

a) Demonstrate commitment to digital transformation strategy, objectives, and activities.
b) Define the purpose and context for digitalization in support of its strategic direction.
c) Provide guidance with conflict resolution, resource prioritization, and escalation.
d) Support human development, re-skilling, and new competencies integration.
e) Balance the human-machine co-working, keeping each one in areas they are best at.
f) Consider eight innovation management principles, described in ISO 56002.
g) Show commitment to ethics, sustainable development, and continual improvement.

The digital transformation policy should fit the organization's culture. The policy should be circulated as documented information to all key stakeholders, including employees, contractors, and relevant external interested parties, as appropriate. The ethics portion of the digital transformation policy may be integrated with an existing ethics policy or code of ethics, and prominently displayed in common areas.

2.6 Roadmap Team

With clarity of purpose, context, vision, and policy, the leadership team should identify individuals who should develop and maintain the roadmap. The Roadmap Initiative Team (RIT) should be knowledgeable about digital technologies, inspection methods, data sciences, business models, and human considerations. The leadership team should define the charter for the roadmap team. For a small business, the leadership team can be the roadmap team, or leverage consultants and partners.

3 Framework

With leadership commitment as evident from the purpose, vision, preliminary external context, and charter, the RIT is ready to get to work and create the roadmap. Just to be on the same page; a roadmap is a "Document that visually describes the activities, timeline, and resources necessary to achieve a strategic objective, such as digital transformation in case of NDE 4.0" and a Roadmap Initiative is "an internal effort by a dedicated team to create the roadmap and keep it current."

3.1 Context

The RIT must define the context along three dimensions with reasonable details and confidence.

The internal context of an NDE 4.0 deployment refers to all elements that lie within the organization, and can be controlled by the leadership, as primary elements of the roadmap, to pursue strategic objectives. It includes products/service offerings, business models, technology portfolio, intellectual property, infrastructure, physical assets, data assets, employee skills, competency gaps, human factors, diversity-equity-inclusion, code of ethics, financial capacity, risk tolerance, partnerships, geographical location, and to some extent preferred suppliers and consultants.

The external context of an NDE 4.0 deployment refers to all elements that lie outside the organization and cannot be controlled by the leadership. The roadmap should provide guidance to continuously monitor the external context and to modify the internal context in response to any changes in the external context. Industry 4.0 or Digital Transformation is the key external driver for the emergence of NDE 4.0. External context includes all the stakeholders in the ecosystem that were not a part of the internal context. The most significant are the market forces within the sector – customers, competitors, and regulatory bodies. It also includes changes in political, environmental, social, technological, economic, legal, Innovation, and pandemic aspects (PESTEL+I+P), that are even broader than discipline of inspection or the industrial sector. With globalization, one needs to consider global trends, even if the internal context is geographically local.

The prospective context of an NDE 4.0 deployment refers to internal and external elements that will emerge over the future whether controlled or uncontrolled. The roadmap should provide guidance to continuously monitor the evolution of desirable, anticipated, and unanticipated items and to modify the internal context towards the desirable prospective context. The core of the roadmap is that portion of the prospective context which includes planned development of products/services, technologies, talent, physical and intellectual assets, and resiliency.

Prospective context should also consider items broader and far-reaching than business. Such as professional obligations, ethical awareness, industry regulations, social responsibility, sustainability, and sustainable development. A simple well-articulated prospective context can be indistinguishable from vision.

3.2 Principles

It is now time for RIT to agree on principles keeping the purpose and context in mind. Here is the starter list derived from Industry 4.0 principles [9]. These principles should guide the team in the selection and development of products, technologies, and competencies.

a) **Interoperability:** The ability of assets, instruments, sensors, devices, inspection equipment, and people to connect and communicate with each other via (IOT)
b) **Information transparency:** The ability of assets and inspection systems to share information (data with semantic interoperability), facilitating interpretation, training, and visualization.
c) **Technical assistance:** The ability of assets to assist in workflow management, inspection automation, and traceability
d) **Decentralized decisions:** The ability of automated cyber-physical inspection systems and assets to make decisions on their own and perform inspection tasks independently; or to seek human intervention in the case of exceptions, interferences, or conflicting goals.
e) **Virtualization:** The ability of assets to generate virtual models of themselves and of other assets in their environment that facilitate the generation of digital-twins.
f) **Real-Time:** The ability of assets to generate datasets that may be retrieved in real-time to support and substantiate decentralized decision-making processes.
g) **Modularity:** The ability and design characteristics of assets to flexibly adapt to different requirements.
h) **Product-Service Offering:** The ability of NDE 4.0 solutions to synergistically merge products and services to create, capture, and distribute substantially enhanced value in order to achieve the purpose of NDE 4.0

3.3 Governance

The leadership team is responsible for the overall governance of digital transformation, which is a little different than traditional governance approaches. A well-governed NDE 4.0 program must satisfy different stakeholders across an organization and be flexible enough to accommodate multiple types of initiatives while ensuring enough rigidity to achieve strategic alignment with purpose and efficiency in execution.

The following principles should be considered while identifying initiatives that go into the roadmap [10]

a) Centralize information about digital initiatives rather than the initiatives themselves.
b) Move from centralized to decentralized governance of digital initiatives as digital maturity grows.
c) Decentralize ideation but centralize idea evaluation and prioritization.
d) Make sure that KPIs and Metrics measure the real impact you want to achieve with each initiative.
e) Avoid siloed solutions by ensuring data compatibility, technical consistency, and continuous integration of new initiatives with existing systems.
f) Implement a “fit-for-purpose” mapping system that recognizes value potential and degree of feasibility for each initiative.
g) Evaluate different scenarios to proactively steward digital initiatives toward full-scale impact.

These principles are in addition to whatever governance system is in place for everyday operations addressing the use of internal standards, alignment with international standards, risk mitigation, transparency, relationship with stakeholders, internal and external communication, chain of command structure, and policy deployment.

3.4 Ethics

Any transformation roadmap must include instances and guidance devoted to providing sound ethics foundations to all the categories included in it. The leadership team is encouraged to engage an external expert on ethics in digital transformation, as the subject is still evolving. This ethical dimension must be an integral part of the governance and aligned with the attributes specific to humans, and human-machine integration.

There are five fundamental considerations on the human side of ethics:

a) **Responsible**: The accountability of all instances involved in the digital transformation should be clearly established in the organizational operations.
b) **Equitable**: All organizational and individual participants should have equal access to the instances and support resources that constitute the ethics foundation of the roadmap initiative.
c) **Traceable**: Accountability for decisions and actions should be clearly established. Records should be generated to properly support any traceability requirements.
d) **Reliable**: The reliability of ethical implementation should be sustained by codes and guidelines, personnel training and auditing, and an ombudsman program.
e) **Sanctions**: Ethics code and guidelines once established should have clearly defined instances, processes, and resources to positively inhibit and sanction ethical behavior violations.

These five considerations are altered in the context of the Human-Machine side of Ethics, where the machines learn and act autonomously, such that the machine output is not entirely in human control.

a) **Responsibility**: NDE personnel will exercise appropriate levels of judgment and care while remaining responsible for the development, deployment, and use of AI/ML in NDE capabilities.
b) **Equity**: The digital inspection system developers will take deliberate steps to minimize unintended bias in AI/ML-based NDE capabilities.
c) **Traceability**: The AI/ML capabilities will be developed and deployed such that relevant NDE personnel possess an appropriate understanding of the inspection technology, development processes, and operational methods applicable to AI capabilities, including transparent and auditable NDE methodologies, data sources, inspection procedure, and documentation.
d) **Reliability**: The AI capabilities will have explicit, well-defined uses, and the safety, security, and effectiveness of such capabilities will be subject to calibration, validation, and POD assessment within those defined uses across their entire life cycles.
e) **Governance**: The digital inspection system developers will design and engineer AI capabilities to fulfill their intended functions while possessing the ability to identify and avoid unintended consequences, and the ability to disengage or deactivate deployed systems that demonstrate unintended behavior.
f) **Data Management**: The NDE personnel will honor the data acquisition, transfer, storage, analysis, processing, security, and ownership/sharing rights as determined by organizational policy and contractual obligations.The leadership team also needs to communicate ethical considerations to all employees, periodically.

4 Roadmap

4.1 Scope and Objectives

The scope of the NDE 4.0 roadmap could be the development of one or more of the following applications depending upon leadership purpose and vision.

Digitalization of NDE (Or Industry 4.0 for NDE): Initiatives directed at the application of Industry 4.0 principles, technologies, and frameworks to improve and expand the realm of NDE solutions in the world. For example: Autonomous drone/robotic NDE for bridges, towers, pipelines; and Digital RT/UT/ET along with Augmented Intelligence for integrity assessment of in-service high-risk assets, such as Turbine parts.

NDE for Digitally Transformed Systems (Or NDE for Industry 4.0): Initiatives directed towards establishing NDE as one of the major data sources for Industry 4.0 needs, pains, and gains [3]. For example: Digital RT/UT/… for an additively manufactured to gain feedback regarding the manufacturing process or Manual UT/ET with digitalized reporting at the end to fuse the data with the data of an automated manufacturing line.

Fully Integrated NDE 4.0 and Industry 4.0: Initiatives directed at integrated development of digitalized NDE capability within digitally transformed systems to fully deliver the promise of Industry 4.0. For example: NDE technologies integrated within smart manufacturing for inline quality assurance with no human intervention; In-situ real-time NDE within additive manufacturing process to control the process for part quality assurance; or NDE and SHM digitally fused to assure service performance and safety.

4.2 Planning Horizons

Based on the purpose, vision, scope, and objectives; and the rate of change in the external context, the roadmap team can define three planning horizons,

Horizon-1 (Operational or H1): This includes projects and initiatives to bring tangible value in a "now and here" timeframe. These tactical-term projects and initiatives may be 3 to 24 months in duration. It is important that H1 initiatives are fully funded through completion.

Horizon-2 (Strategic or H2): This includes projects and initiatives to bring tangible value in a "Near future, embracing emerging trends" timeframe. These strategic-term projects and initiatives may be 1 to 5 years in duration. Strategic-term projects and initiatives are intended to generate and capture significant stakeholder value when implemented. H2 initiatives may have proof of concept or demonstrator technologies identified and funded under H1.

Horizon-3 (Visionary or H3): This includes projects and initiatives to bring tangible value in a "Pursuit/tracking technology evolution in line with purpose" timeframe. These long-term projects and initiatives may exceed a period of 3 years. These should address ambiguity and uncertainty, particularly in an external technological context. H3 Initiatives may have demonstrators identified under H2 and exploratory studies funded under H1.

Leadership must assure alignment and continuity of H1, H2, and H3 outcomes through funding mechanisms.

Caution: The three-horizon model when applied to transformation or any significant change, needs special care because it is hard to see clearly that far. The H2 and H3 planning carries a significantly higher level of uncertainty and will likely require major modifications and pivots, both technological as well as business models, as it evolves.

4.3 Dashboard

The leadership team should identify a set of KPIs and metrics, in an integrated dashboard or scorecard, aligned with the MTP. The performance should be monitored by the leadership. These KPIs should cover the four prominent categories in line with a balanced scorecard viewpoint.

Value Creation perspective: These are tied to the internal processes supporting the primary purpose of implementing NDE 4.0. It could be in terms of performance, safety, capability, reliability, speed, workflow efficiency & effectiveness, accelerated learning and certification experience, Asset design improvement, asset quality, waste reduction, etc.

Customer perspective: These are tied to the value delivered to the customer – enhanced safety, turn time, cost of operations, etc.

Employee perspective: These are tied to renewed respect for NDE, employee learning and development, as well as improved inspector safety and support.

Financial perspective: This is the traditional quantification of impact on top line and bottom line. This most popular set of metrics should not be looked at in isolation, but through the natural and profound interconnection with the other three perspectives.

In addition, one may choose to add tracking of strategic progress and risk management as add-ons. Ineludibly, all MTPs and metrics defined for roadmap initiatives should take into consideration any human perspective of NDE 4.0, including ethics.

H1 initiatives should have tangible and definable metrics. H2 initiatives should have a measurable metric without a target assigned. H3 initiatives should not have any measurable goals, other than total investment limits. The KPIs represent quantitative or qualitative parameters that show how effective are the operations in achieving the objectives. Metrics represent quantitative or qualitative parameters that serve to monitor the status of any specific process.

4.4 Draft Roadmap

Roadmap essentially constitutes a custom portfolio of technologies and enabling initiative, specific to the target markets – including industries and geographical regions. It should consider the following elements:

(a) **Synergistic planning horizons**: Proper balance and blend of H1/H2/H3.
(b) **Digital technologies readiness**: Based on technology adoption curves and technology surveillance process for the state-of-the-art in R&D and practical applications.
(c) **Smart workflows**: Integrating devices and communication protocols to accelerate the value generation process.

(d) **Smart NDE Applications**: AI permeation or readiness for AI should be a part of the technology portfolio.
(e) **ICT infrastructure**: should be specifically addressed as one core element in any roadmap deployment initiative.
(f) **Decision support systems**: Technologies that generate relevant knowledge to support decision-making processes should constitute a desirable element in a technology portfolio. Dashboards and scorecards with adequate UX design and relevant KPIs may serve as interfaces to guide and facilitate those decision-making processes at all relevant instances.
(g) **Pilot programs**: Devoted to field validation of innovative solutions to decide which ones can be refined and which ones should be pivoted.
(h) **Deliberate frequent reviews**: which can be built in as an integral part of activities to account for uncertainty in planning, execution, and outcomes; and create opportunities for revisions at a frequency higher than the normal strategic cycle.

Based on the diverse requirements of the NDE domain, the landscape of technologies discussed is graphically shown as a mind map in figure 2. 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.

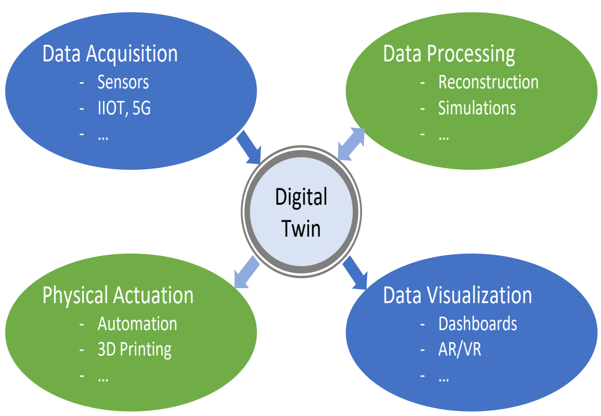


Figure 2: *Mind map for NDE 4.0 technology landscape [6]*

Data Acquisition and Handling includes Industrial Internet of Things, Digital twin, thread, and weave, Semantic interoperability and ontologies, 5G, Blockchain, Data security and Sovereignty, Data integrity, Traceability, Revision safe data formats and storage, Data Transparency, etc.

Data Processing and Computing includes Big Data, Cloud Computing, CAD/CAM/CAE/BIM, Simulation, Reconstruction, and inverse engineering, Smart Handheld devices, Edge Computing, Quantum computing, Artificial intelligence, Machine Learning, Deep Learning, Generative AI, Algorithms (heuristic, model-based and statistical), Image analysis/signal-information-raw data processing, Sound analysis/signal-information-raw data processing, etc.

Data Visualization includes Extended Reality (AR/VR/MR/PR/XR), Dashboards, Volumetric Displays, etc.

Physical Actuation, includes Automation, robotics, drones, Automated Inspection Systems, Additive manufacturing, etc.

In addition to these, the RIT must consider need for **Enabling Hardware,** such as: Special Hardware for AI, Telepresence, Biodegradable sensors, DNA Computers and Storage, Smart Dust, Neuromorphic Hardware, Carbon-based transistors, Nanotube Electronics, Customized analog/digital sensor development, etc.

Vertical and Horizontal Human-Systems integration of all these requires the inclusion of Virtual Personal Assistance – Conversational, Gesture, Smart workspaces and UX Design, Interface Layers and Standards, Brain-machine interfaces, Responsible AI, Intelligence augmentation and Machine assisted decision making, Cryptography, (Symmetric-key, Quantum, Public-key, Post-Quantum)

RIT should not discount the role of **new protocols and interfaces**, and any **new regulatory constraints**.

4.5 Roadmap Validation

Every roadmap needs validation. This is a two-step process.

Internal Validation comes in form of a review of the roadmap conducted by the leadership team and grounded in past experience. One of the possible ways is to view the alignment in inverse order, initiating with the learning and growth, and moving upward toward the financial perspective. Another is to play what-if scenarios. Third could be cross-check with historical performance or know-how of the advisory board.

External Validation requires engaging with key external stakeholders. One possibility is to engage with trusted customers on what-if scenarios. Another one is benchmarking with non-competing organizations.

Supplementary insights to improve the roadmap content may include a) Team structure, roles, and membership expertise, (b) Sponsorship and funding requirements including number, profiles, and amounts to be obtained, (c) Inclusion of specific initiatives under current R&D activity to improve their alignment with MTP, (d) Supplementary partnerships or alliances, and (e) NDE 4.0 Ethics Check.

5 Execution

Now the rubber meets the road. RIT must execute according to the validated roadmap with the realm of principles agreed upon with the leadership team.

5.1 Resource Allocation

Leadership commitment essential to support NDE 4.0 for it to be successful, is exhibited through the allocation of resources and progress reviews. Leadership should be prepared to provide resources, further development of new skills and competencies, as well as new tools and methods. These resources are categorized as follows and should be identified in the roadmap.

General Resources: This refers to all tangible resources excluding people.

(a) **Financial**: Funds the projects and activities, which may come from internal or external sources.
(b) **Partners/suppliers**: Support network with capabilities that do not exist in house.
(c) **Infrastructure**: Tangible or intangible assets for installation, operation, and deployment of projects or initiatives. This includes (i) physical equipment and systems, (ii) digital devices and systems, (iii) information systems, and (iv) communication.
(d) **Equipment**: Tangible assets required to develop the required knowledge and technologies in support of the projects and processes. IOT-enabled equipment should be preferred over stand-alone units.
(e) **Technologies**: Access to a portfolio of proven fundamental technologies for developing prototypes. Annexure-C provides a starter list.
(f) **Knowledge**: Know-how and know-why of existing products/technologies in a documented form.

Human Resources: This refers to people with relevant skills, competencies, mindset, and capacity to support the roadmap [11,12].

Skills refer to a person's ability to perform a certain task, such as an NDE UT practitioner's skill to scan a weld using a phased array transducer within a pressure vessel. Skills may be classified as:

(a) **Trade Skills** (or Hard Skills): They provide the foundation for the deployment of NDE 4.0 projects and initiatives. They include (i) NDE-specific physics, (ii) General Science and Mathematics, (iii) Electrical, mechanical, and systems engineering, (iv) Technology integration & application.
(b) **Digital Skills**: They provide the capability to integrate commonly available digital systems with foundational NDE systems. They include using devices and handling information, programming, creating, and editing digital content, digital communications, digital transactions, and online security.

Data Skills: They provide the capability to establish data organization and reliable statistical and deterministic data processing. commonly available digital systems with foundational NDE systems. They include converting data to information, fusing information, and training artificial intelligence solutions.
Soft Skills (or people skills) : They allow improved performance both on an individual basis and as a workgroup to manage a project or initiative successfully. They include: (i) Mindsets - self-awareness, character traits, and attitudes; (ii) External relations - social awareness, team effectiveness, interpersonal people skills, social skills, communication skills, career attributes, emotional

intelligence skills, and responsible online behavior (iii) Management Skills - planning, communicating, decision-making, delegating, problem-solving, conflict resolution, motivating and negotiating (iv) Balancing and blending human-machine coworking at both physical and intellectual levels.

Competencies refer to the capability of applying or using knowledge, skills, abilities, behaviors, and personal characteristics to successfully perform critical tasks, specific functions, or operate in each role or position (See figure 3). Competencies are thus underlying characteristics of people that indicate ways of behaving or thinking, which generalizes across a wide range of situations and endure for long periods of time. Performing the role of an NDE Level III to manage all NDE-related processes within a company is an example of a competency.

Figure 3: *Performance depends upon several factors [13].*

The roadmap team should identify roles and their description with all relevant skills and competencies necessary to perform it successfully in the context of the roadmap initiative. These role descriptions should be integrated by each operative area and aligned with the objectives of the roadmap, validated by the leadership team. A role often missed is that of a Chief Engineer, who acts as a systems integrator and understands technology, application, and evolutions. The role may not be necessary but, it helps significantly to have a technical focal at the leadership level. Once those role descriptions are established and validated, a gap analysis should be performed for everyone assigned to the role to define his/her development plan.

For specific projects and initiatives, the completion of particular certification(s) may be required. Those requirements should be identified and integrated into the consolidated training program where there is an already available certification program. For certain instances, where no generalized certification programs are available, the development of a tailor-made certification program should be considered, or a well-documented exception justification by appropriate stakeholders.

5.2 Technology Management Process

Projects and initiatives on the roadmap should be managed with rigor of technology or innovation management depending upon the degree of uncertainty. The steps include:

a) **Technology surveillance/vigilance**: The search in the environment for signals and indications that allow the identification of threats and opportunities for technological development and innovation. This may include benchmarking, Markets/Customers research studies, and technological monitoring.
b) **Technology planning**: The development, review, and revision of a technology portfolio that allows the organization to select lines of action to achieve a competitive advantage.
c) **Technology alignment**: The organized integration of technology in all the organization’s operations. It also includes the alignment of the technology plan with the business strategy.
d) **Technologies and resources enablement**: The procurement, inside and outside the organization, of technologies and resources necessary for the execution of the projects in the portfolio. This may include a) Technology acquisition (purchase, licensing, alliances, and other applicable methods). b) Technology assimilation, c) Technology development (technological research and development, technology up-scaling, and other applicable instances), d) Technology transfer, e) Technological projects portfolio management, f) technology-involved personnel management, g) financial resources management and h) knowledge management.
e) **Technology patrimony protection**: The safeguarding and care of the organization's technological patrimony, generally by obtaining intellectual property rights. This includes activities intended to capture, transform, protect, and preserve the intellectual property generated.
f) **Technology deployment**: The implementation of innovation projects until the final launch of a new

or improved product/service/experience to the market, or the adoption of a new or substantially improved process within the organization. It includes the commercial exploitation of such innovations and the organizational expressions that are developed for this purpose.

NDE 4.0 also requires significant innovation management which entails a match-making between needs and ideas. Guidance for innovation management can be found in ISO 56002 [14] and InnovatePedia [15].

5.3 Operations

Operations enable the transformation of intentions and plans, into securing resources, to produce verifiable results. An organization may already have them in place and should be able to use as many of the existing processes as practical. All processes to facilitate digital transformation should align with success metrics (KPIs) defined under the primary dashboard perspectives.

Financial: These processes manage the generation and use of funds that make the digital transformation viable. Financial management may include, but is not limited to:

(a) **Data monetization**: that allows a business proposition around the transfer of data.
(b) **Portfolio approach**: for aggregation and diversification of investment portfolios.
(c) **Intangible assets**: generation, maturity, integration, and protection for a competitive edge.

Customer: These processes manage the relationship with the most significant stakeholder group, to obtain the intended outcomes of the roadmap initiative. Customer relationship management may include, but is not limited to:

(a) **Customer insight**: through continuous empathic feedback intended to capture valuable insights for improvement of (i) the roadmap and resulting value creation for the customer, (ii) relationship, and (iii) internal processes for value creation.
(b) **Impulse value generation perception**: using communication processes intended to close the perception gap between the true and perceived value delivered, aimed at minimizing the risks for the deployment and adoption of the roadmap initiative.
(c) **Customer education**: to provide support through the guided diffusion of knowledge, skills, and competencies and facilitate the deployment and adoption of the roadmap initiative.

Value Creation through internal processes: These processes enable the creation, capture, and distribution of value to satisfy stakeholders' needs, including customers, and meet business strategic goals. Value management may include, but is not limited to:

(a) **Value chain management**: is the basic traditional approach to the creation, capture, and distribution of value and is at the core of almost all management perspectives.
(b) **Value network management**: expands the value chain management to a wider ecosystem, and how tangible and intangible value is managed through knowledge sharing, sometimes in real-time.
(c) **Technology management**: as described above.
(d) **Ideation and Innovation Management**: process and techniques at the core of design-thinking initiatives to stimulate creativity and value through novelty.
(e) **Validation/Qualification**: constitute the assurance that processes, systems, facilities, equipment, and people contain the elements required to properly perform their functions.
(f) **NDE-specific processes**: starting from the data acquisition through sensors, networked within NDE systems, that provide information from assets, and their environment, and enable decision making.
(g) **NDE certifications**: which guide validation and provide evidence that NDE systems and personnel have the necessary competencies based on standardized certification requirements, (such as ANSI/ASNT CP-189, ISO 9712, etc,) or based on industry/company/application specific requirements.
(h) **Regulatory compliance**: with all the applicable regional legislation and industry-specific requirement within the roadmap scope, monitored continuously, and used to

update the portfolio and so it is always relevant and useful.

Learning and Growth: These processes help formulate and implement the development of human resources and organization knowledge base - the intangible assets of the organization to support value creation. Learning management may include, but is not limited to:

(a) **Talent management**: from the development of individual skills and competencies, and organizational career tracks, to succession planning, including incentives to retain and reinforce talent.
(b) **Knowledge management**: from development and containment of documented know-how and know-why, including procedures, and databases, to performance and organizational learnings.
(c) **Continuous improvement**: seeking to improve every process by enhancing the activities that generate the most value for the stakeholders, while removing waste. It completes the value creation loop that transvers the four perspectives

Risk and Uncertainty Perspective: These processes help assess and mitigate risk in technology development and market capture. Risk mitigation may include, but not limited to

(a) **Portfolio Management**: as discussed above
(b) **Technology reviews**: using a phase-gate process with competent experts as gate keepers.
(c) **Marketplace benchmarking**: to assess the needs, gaps, and competitive position.
(d) **Customer-shared vision**: to assure certain market share and investment recovery.

5.4 Roadmap Diffusion

The roadmap needs acceptance across the organization and communication to relevant external stakeholders. This requires structured communication to promote and garner support for success.

Internal Diffusion refers to topics within the organization, where the leadership team has a relatively higher degree of control.

(a) **Overcoming internal barriers**: such as adverse organizational culture, inadequate organizational structure, internal politics, attitudes, or communication barriers. Analysis tools such as force-field diagrams may be used to identify and prioritize actions.
(b) **Transparency**: through mechanisms aligned with the purpose of the roadmap initiative and in adherence with applicable company policy on information sharing.
(c) **Authority and autonomy**: to execute specific activities as deemed essential for success.
(d) **Employee engagement**: through communication, alignment of personal growth with company growth, incentives, and inclusion in decision making.
(e) **Teamwork engagement**: through an environment of mutual trust among engaged employees.
(f) **Ownership commitment**: as demonstrated through their personal involvement in the roadmap**.**

External Diffusion refers to select engagement with external elements through networking and influence. The roadmap communication strategy should integrate an analysis of all relevant stakeholders in order to properly diffuse the messages to each type of stakeholder and prevent adverse impacts to the roadmap initiative derived from the action of ill-intentioned social agents.

(a) **Overcoming external barriers**: such as legal, regulatory, market perceptions, industry level politics, IP rights, etc.
(b) **Go to Market**: strategy with limited exposure of the roadmap to select customers.
(c) **Marketing, diffusion, and adoption**: strategy to capture share early.
(d) **Customer engagement**: to capture their requirements and improve their utilization of your products/services.

Regulatory engagement: An early and active participation in relevant regulatory instances is strongly recommended to guide and positively influence the evolution of regulatory elements relevant to the roadmap scope.

6 Improvement

The roadmap must continuously improve to fully capitalize on opportunities and minimize risk. This requires a periodic performance evaluation of leadership, planning, support, and operations, with full awareness of changes in external and internal context, and reassessment of prospective context. This can be achieved as follows.

6.1 Acceptance

Information and knowledge required to evaluate the acceptance of the roadmap should be regularly compiled and analyzed. This information and knowledge may take the following form:

(a) **Massive Transformation**: performance as noted by KPIs, and metrics aligned with the Massive Transformative Purpose and scope, as well as stakeholder feedback on progress.
(b) **Full KPI dashboard**: with quantitative parameters for the objective performance assessment of various processes categorized under Business or ESG KPIs and metrics.
(c) **Barriers and limitations**: that impede the advancement of roadmap initiatives should be identified, documented, and addressed adequately.
(d) **Organizational structure:** that constrains the execution of the roadmap should be identified and addressed.
(e) **Resource constraints**: that limit the execution of the roadmap should be identified and addressed.
(f) **Setbacks and Failure**: when properly focused by leadership constitute important opportunities to derive learning processes and to generate improvement opportunities.

6.2 Analysis

Roadmap deployment, review, and changes should be data-based. The leadership Team should implement and institutionalize a structured analytical approach to process and analyze the KPIs and metrics.

(a) **KPI Analysis**: of data captured on pre-determined items over a period. It includes Business indicators, and ESG/SDG indicators. The analysis may include causality validation, context validation, benchmark validation, or segmentation validation.
(b) **Root cause analysis**: of KPIs, their trends, or unintended discrete events to support any decision-making process derived from it.
(c) **Impact scope analysis**: to deeply survey the KPIs and metrics for value created by roadmap. The impact can be analyzed from two perspectives – business value and social value, even if they go in opposite directions.
(d) **Trends and projections**: using appropriate numerical methods, statistical analysis methods, and algorithms to generate projections and improve planning processes.
(e) **Scenario-based forecasting**: for critical to business KPIs, to generate response protocols and contingency plans. Uncertainty may be accounted for by making estimates from conservative and aggressive assumptions.
(f) **Best practices spotlight**: that support the roadmap development, execution, and diffusion; from internal or external sources. Note: Best practices do not imply that they are not subject to improvement.

6.3 Review

Review complements the analysis to extract the necessary knowledge and decide on actions for improvement and sustainability of the roadmap initiative. The review process should consider, but not be limited to:

(a) **Periodic reviews**: at a frequency predetermined by the leadership team, with a formally defined agenda and participation.
(b) **Contingent review**: triggered by an event that significantly alters the external or internal context making a part of the roadmap irrelevant. Leadership should define the focus, agenda, and participation for the specific review.
(c) **KPIs review**: integrated with the periodic or contingent review to assure that dashboards are designed to capture what matters.
(d) **Communication review**: to detect opportunities for improvement in creating stakeholder's perception.

6.4 Refine

The roadmap should include a category of activities devoted to learning and improvement, associated with the planning horizons.

Continuous Improvement: This first improvement category in the roadmap achieves small changes in specific roadmap projects, all the time based on simple feedback. Those small changes should be based on the same objectives and the same technology used to define the initial roadmap initiative. These improvements can be executed at the operations level, and are typically limited to H1.

Technology Pivot: This second improvement category in the roadmap may be in response to the perceived or foreseeable evolution of the technological environment and include projects devoted to achieving use case learning and alternate options generation. Those changes should be based on the same objectives, but with alternate technology options. These improvements can be executed at the leadership level, and typically for H1/H2.

New Direction: This third improvement category in the roadmap include projects devoted to new focus, new use cases, a revised technologies portfolio, and/or revised business models and value propositions. Those changes should be based on new objectives, and they may or may not comprise changes in the technology used in relation to the initial roadmap initiative. These improvements are decided by the leadership team or key stakeholders on the recommendation of the leadership and may constitute a significant change to the roadmap. These changes start with a revision of H2/H3, and then trickle down to H1. Sometimes this even calls for change in the leadership team.

A well-tuned review and improvement cycle is a sign of committed leadership, and just as important as a well-defined roadmap. Considering that technology evolution is so rapid and investment capacity for any organization is limited, this step plays a significant role in accomplishing the desired change.

7 Example: Next Generation NDE Equipment

This is an example to demonstrate how an NDT OEM can build the roadmap to bring Industry 4.0 class NDE equipment using guidance from this book.

7.1 Orientation

The Vice President of Engineering happened to attend the basic course on NDE 4.0 at a conference, which built an anxiety to do something as the world appeared to be changing. His conversation with the CEO led to the start of this program. They included VP of engineering and VP of business development to form the 4-member leadership team.

7.2 Setup Leadership:

CEO initiates: The leadership team motivated a few managers and engineers to read the books "World of NDE 4.0" and the draft version of an ICDNT roadmap guidance document – a predecessor to this paper, with intent to transform the product portfolio

Purpose defined: Leadership team defined the purpose of their roadmap initiative as **"***Create next generation of NDE systems with digitally enhanced capability and reliability*."

The objective is to disturb the competitive landscape in their primary market (nuclear, oil, and gas), increase market share in other secondary markets (aerospace and transport), and provide entry to market in at least one additional industry.

External context framed: Extensive list of known and likely aspects were identified, dominated by increasing demand for (a) inspector safety in hazardous environments, (b) rapid data acquisition, and (c) reliable interpretation.

Vision drafted: Based on the purpose and external context, the leadership drafted the vision as "*Autonomous inspections with dependable decision support system*."

Company policies enhanced: Policies were revised to include managing and securing data as tangible property, ethical considerations around use of AI, employee learning and development for the future, engagement on use of customer owned data, data breach, and business continuity.

Roadmap initiative team identified: The Chief Technology Officer was identified to lead the team with Chief Engineer as deputy. Included in the team were the Director of IT, Director HR, three subject matter experts, and a newly hired programmer. The CEO will continue to be the executive champion.

Internal diffusion: This intent was shared with a select few employees only for the confidential nature of the activity. Those exposed were sworn to secrecy until further notice.

7.3 Setup Governance

Internal context identified: Team took a couple of weeks to understand the current state of the company in context of the vision. Gaps in performance capacity and competencies were identified as critical to success. Years of six-sigma had eroded all surplus capacity.

Their training was traditionally focused on jobs at hand. The only positive outcome from too much lean is that the company had financial resources to invest. The culture of ethics just needed an expanded awareness around new issues with digital transformation. The team discussed all the normative references for relevance.

External context refined: Another couple of weeks were invested in analyzing the external business environment. Starting with extensive market insight, benchmarking, eco-system mapping, and in-depth PESTEL+I analysis, the team identified one serious political change, one socio-economic shift, one legal concern, and three new external stakeholders with a possibility of one new business model - *servitization* (access to the company's product as an on-demand service).

Prospective context defined: Team held a 2-day workshop to speculate the future based on PESTEL trends and market insights, with an external facilitator, professional at this. It focused on dual transformation – digital and sustainability, with business resiliency as an important consideration. After some deliberation the social responsibility was kept out of scope for the purpose identified.

Several undesirable incidents were identified as possible with two of them likely to occur, needing upfront attention in the roadmap.

This was the most useful exercise during this step of governance setup.

NDE 4.0 Principles accepted: All principles were found to be usable as described, with highest emphasis being on cyber-security, for the need to manage customer data and trust.

Governance guidelines prepared: A new formal document was created to document the above aspects, compatible with the existing operating system. This was reviewed with the leadership team, and marked for annual review, to keep it current.

Code of Ethics revised: It now includes digital aspects, with appreciation that data and algorithms for automation will likely be biased. All the suggested guidelines in this book were acceptable as described.

Digital Transformation Review Board was setup to assure governance and adherence to principles, as documented. This is based on a design review board and materials review board. The new board, which is essentially a subset of the roadmap team, was tasked to draft their expectations.

7.4 Create Roadmap

Roadmap initiative kicked off: The team identified roadmap template, held three facilitated ideation sessions to generate data, and established quarterly review cycle. Only one business unit was involved.

Deliberation led to a strategic decision to have 25% of the investment into 2-3 visionary trendsetting projects, 40% for smart forecasting class of development, and 35% at the agile following level. This is unusual, but desirable in this case, given the external context, an opportunity to bring mature digital technologies to the NDE sector, and available financial resources as well as risk capacity.

Scope defined: The primary focus is on digitization of the inspection product and digitalization of NDE processes. This came with an understanding that there will be some digitalization of the manufacturing process along the way. All of this should pave way for total digital transformation later.

Horizons and objectives defined: Horizon-1 objectives included identification and validation of core technologies on existing inspection platforms within 6-18 months. Horizon-2 objectives included autonomous inspection systems and decision assist as separate capabilities within 24-36 months. Horizon-3 objectives included integration of autonomy and intelligence.

Dashboard established: Several suggested KPIs were already in use at this company for business operations. From product standpoint, the additional metrics included autonomy and decision accuracy as outcome indicators and portfolio ROI and digital skills as leading indicators.

All technology options were kept on the table at this point, with intent to build asset digital twins on 'as you go' model.

Roadmap developed: The roadmap is developed using a proprietary tool, with the capability to export as Excel or PowerPoint for external sharing.

Roadmap reviewed and revised: Digital transformation Review Board took a deep dive into the roadmap and did not approve it in the first round. There was poor alignment with several of the NDE 4.0 principles agreed upon upfront.

The roadmap team went back and revised the roadmap to include additional technologies to the planned products. This led to an increase in resource requirements that CEO was not prepared for.

Another round of revisions led to the inclusion of some very creative approaches: (1) Moving some of the newly added technologies to address NDE 4.0 principles into horizon-2 for the subsequent revisions of the product. (2) Adding digitalization to manufacturing process for productivity improvement. (3) Using state government grants for investment in specific manufacturing technologies to offset the cost of productivity improvements. (4) Using supplier financing for introducing their tech into the product. (5) Making advance sales at discounted price to the trusted customer. All this also assumes that initial release of products will generate profits to meet the promises along the supply chain and also fund the subsequent investment. This was an additional financial risk item in the roadmap.

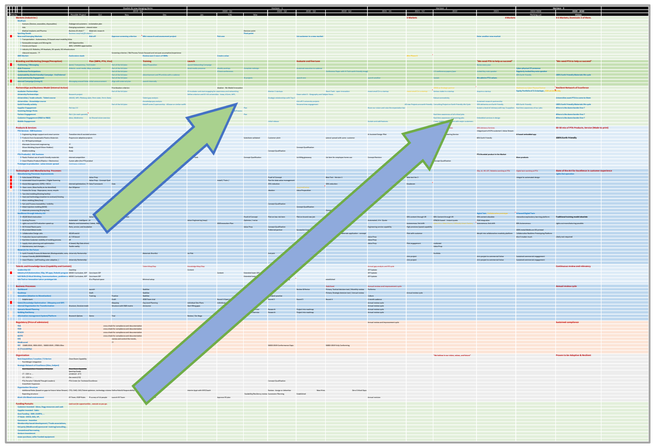
Essentially, the team learned what makes the transformation hard to accomplish and how to address them in a manner of small steps, supported with a serious and solid risk analysis and mitigation plan.

Roadmap validated: Internally, a different set of individuals was tasked to review the details from bottoms-up and top-down view. They identified three assumptions that were high risk. CEO added risk mitigation actions to the roadmap with additional resources.

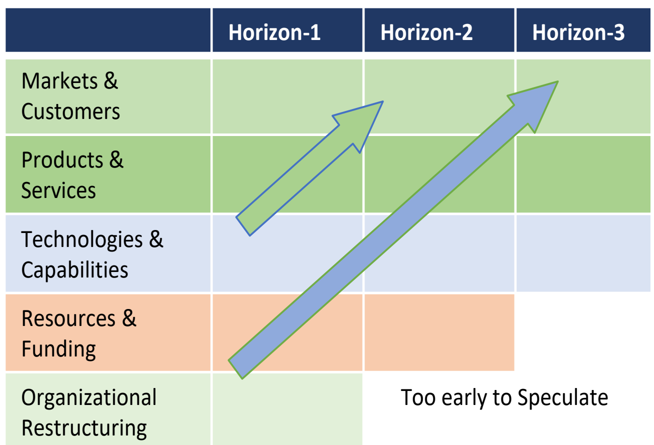
The trusted customer was engaged for external validation. She had already addressed a few unknowns and refined the priorities during funding conversations.This was a very fruitful exercise. It also alluded to a new role for Digital Products Director in the company.

Roadmap approved: Leadership signed it as approving body. Entire team signed it as show of commitment. It was marked confidential – NEED to KNOW BASIS.

Here is a snapshot of the roadmap that deliberately hides proprietary details.



The graphic here provides a high-level view of the structure, showing meaningful connection from lower left to upper right.



7.5 Prepare Organization

Technology Management process exists in the company. Patrimony protection was added. New roles connected with digital competency were added to the review team for stage gates. Review check lists were enhanced with NDE 4.0 principles and digital ethics checks as per the approved governance guidelines.

General resources estimated. Funding, the biggest one, was estimated based on technology plans, and plausible sources. It forced some reprioritization in favor of low hanging fruit to make the entire program sustainable. Several new suppliers were identified for digital technologies, which also required adding an addition line item in roadmap for supplier qualification. The existing infrastructure was found to be adequate. The biggest gap was in knowledge, particularly the integration piece. The review process was strengthened with additional risk mitigation actions. There is no data set either to try out the AI/ML side of development.

Human talent estimated: This was a bit of a challenge since there is no guidance on the quantification of human talent requirements. This guide only provides a list of skills. An initial swag indicated the need for 3-5 additional engineers with digital and data management skills. It also identified a need for leadership training on the digital side of organizational behavior.

Another major gap identified was in integration skills, since there is no single person who had all three skills - inspection method, diverse applications, and data skills. This firmed up the opinion to create a new role for Digital Products Director. With not enough understanding for such a role in the marketplace, senior leaders created a provisional position description and began the search for a close match. No new certifications were identified at this point.

Leadership demonstrates commitment: Budget was allocated and a weekly cadence for meetings was setup to track progress. These meetings were set up for early in the morning when the CEO is likely to be available in person as well as mentally. A separate room was dedicated to managing operation with visual dashboards/whiteboards.

7.6 Transformation

Value management: Since the focus is more on creating autonomous products and not in the automation of manufacturing process, the value creation is embedded in innovation, design, and technologies of the deliverables. The important items addressed in this section are technology management, validation, and qualification, followed by certification and regulatory approvals. The procedures are being revised to include extensive digital context. Each process change will go through single pilot use before formal approval as standard work.

Customer engagement: The trusted customer now plays the role of an advisor and has also offered to be the beta user.

Risk and uncertainty management: Traditional risk matrix is being used considering likelihood, impact, and prevention opportunity to prioritize. Additional rigor was added to the technology reviews at phase-gate process. An external IT form has been engaged for cyber-security aspect of the product and likely a series of cloud-based applications. The business development team is on high alert for early market entrants and value perceptions for such products, so they can be priced fairly.

Financial management: Most systems are in place. The team still needs to figure out data monetization models.

Learning and growth: The team is continuously learning through online courses, and they discuss subjects over weekly lunch-n-learn meetings. They have also identified a set of courses for others to take when it becomes a company-wide initiative. The HR and IT directors have been tasked to continuously refine the processes in place to detect the need for specific skills. This will evolve over the next many months as learning continues.

7.7 Learn and improve

This is a new initiative, and the improvement cycles will likely begin in a year or so. The leadership team does understand the need for different levels of analysis and change.

8 Summary and Outlook

NDE 4.0 is a case of massive transformation. It requires digital technologies to be integrated into the inspection systems, digitalization of workflows, and integration of NDE workflows within value streams. This paper is all about **HOW** to digitalize and digitally transform the NDE system. [1] elaborated **WHY** is it important for almost everyone in the NDE eco-system to embrace it and [3,4] elaborated **WHAT** digital technologies in NDE can help improve design, manufacturing, maintenance, and safety.

Roadmap for digital transformation does have some parallels with traditional roadmaps and transformational efforts, just with the added complexity of uncertainty, major resource investment in technology and talent, and discipline-specific attributes. This paper is guidance document, and every user can adapt to their context, purpose, and limitations.

Fernandez, Hayes, and Gayosso in [12] envision how NDE systems are being disrupted by digital transformation processes as follows: "*In the first NDE lessons often apprentices are still taught the four indispensable elements in a NDE test system (An energy source, a test object, the interaction between that energy source and the test object and a recording medium for this interaction) and while analyzing how the test system does not function in the absence of one or more of those four elements ineludibly a fifth presence, human intervention, often not addressed for its explicit omnipresence which needs to assimilate and capitalize a rising sixth presence, (digital technologies, (including elements such as telepresence, digital aides-de-camp or assisted analysis based in) artificial intelligence, which may be a source of extraordinary opportunities and an unmistakable ally, if properly assimilated, to assist humans to unleash the power of their talent and ingenuity to create and deploy the next generation of NDE systems in the following years*" This transformation has the potential transform for good our discipline and the world.

The NDE 4.0 vision can now become reality with advanced computing and big-data capabilities, using an approach proposed in this guideline paper.

Most importantly, this transformation needs to be viewed as a journey and not a project or a single deliverable goal. It could take a few years depending upon the organizational internal and external context, resources, and commitment to sustainable growth through change. Where does the journey end will not be clear in the beginning, but you will know when you get there. To some, the world of NDE 4.0 appears overwhelming, but a roadmap that breaks down the holistic view into achievable goals, provides a means to successfully take on this journey.

Acknowledgment

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AI for NDE 4.0 - How to get a Reliable and Trustworthy Result in Railway Based on the New Standards and Laws.

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Abstract

The potential of artificial intelligence (AI) in our modern society is virtually boundless. However, alongside this potential, we are witnessing an increase in challenges and risks within the field. In Europe, these concerns have spurred discussions leading to the development of the AI Act, a European law designed to harness the potential of AI technology while safeguarding personal rights and security.

This article will delve into the significance of AI in non-destructive evaluations (NDE) and (also) the necessary steps to establish reliable AI solutions. It's essential to note that this process should not be perceived solely as a regulatory requirement but as an opportunity to enhance value, ultimately enabling the creation of innovative maintenance concepts. As an illustrative example, we will explore the use of AI technologies in rail testing, a part of the ongoing AIFRI project in Germany.

Keywords: *ND; Reliability; POD; AI; Railways; predictive maintenance*

1. Introduction

When embracing any new technology, the central question often revolves around on how to harness its full potential while mitigating its drawbacks. Achieving a perfect balance is admittedly impossible, but history has shown that humanity has consistently embraced significant developments such as the wheel, the letterpress, and various industrial revolutions. Artificial Intelligence (AI) stands as a transformative technology with the potential to reshape our world in profound ways. This very potential prompts people to consider AI in contexts like Industry 4.0 and Non-Destructive Evaluation 4.0 (NDE 4.0).

However, it's crucial to understand that NDE 4.0 represents more than just adopting a new technology; it signifies a revolution. It's about creating an environment that fosters seamless collaboration between humans and technology. AI plays a very important role in NDE 4.0 by revolutionizing the way the inspections are carried out for the integrity of materials, structures, and components. AI algorithms can be applied to various NDE methods, such as ultrasonic testing, radiography, and eddy current testing, to automate and enhance the inspection process. By analyzing vast amounts of data with remarkable speed and precision, AI can detect defects that might be challenging for human inspectors to identify. This leads to several benefits, including increased inspection efficiency, reduced human error, and the ability to detect certain defects which may be missed by manual inspections. Additionally, AI-driven NDE can facilitate in improving safety, and reducing downtime in industries like aerospace, manufacturing, and infrastructure.

Even though, AI presents significant advantages in NDE 4.0, there are potential drawbacks and dangers associated with its adoption. One major concern is that the excessive dependence on AI systems might lead to reducing the expertise of human inspectors and the critical evaluation needed for certain inspections. Moreover, the use of AI in NDE depends heavily on the quality and diversity of the data on which the AI is trained. Any discrepancy in the training data could influence the AI decision-making, potentially leading to false positive or false negative results. There is also the problem of security issues, in the event of these AI systems are hacked or manipulated. This leads to the loss in integrity in inspection processes and the safety of critical infrastructure.

This is precisely why discussing the regulation of AI in the realm of NDE is not only necessary but also highly valuable. It's about establishing the right framework to ensure that the incorporation of AI into NDE processes is not only regulated but optimized for the benefit of all.

1.1 Standardizations and regulation in Europe

The European AI-Act [1] is currently in the process of being reviewed. This act reflects the European approach to harness the potential of AI technologies while remaining in alignment with European values and basic rights. This broad development spans various sectors, from medical diagnostics to financial decision-making. While the field of NDE is a relatively small part of this extensive discussion, it is still valuable to examine the processes and incorporate beneficial approaches from other domains.

The utility of these approaches largely depends on the specific application area. Therefore, the initial discussion will focus on general aspects, such as the trustworthiness and applicability of the AI-Act to NDE, with a particular emphasis on railway testing. Despite the potential risks associated with AI misuse, the AI-Act provides a mechanism for risk analysis within its designated scope. It categorizes AI applications on a scale ranging from minimal risk to high risk as well as unacceptable risk.

From the perspective of NDE, rail inspection plays a crucial role in ensuring the integrity of critical railway infrastructure. As per the AI-Act under Annex III, railways are not classified as critical infrastructure, whereas streets and highways are considered highly critical components of our society. Nevertheless, the comparable nature of these sectors underscores the importance of careful consideration, especially when taking into account that the Act is still under development.

The Act also mandates a declaration of conformity, which is not new in the field of NDE. However, the implications of the AI-Act for users need to be understood. The Act delegates the responsibility of planning AI approaches, making decisions, and defining the various fields of application to the member states of the union. In Germany DIN, an independent platform for standardization in Germany, is concerned with this topic. From their perspective, the DIN Normungs roadmap [2] serves as a valuable tool for comprehending the requirements and needs in the implementation of AI. DIN provides a platform for experts to discuss AI's requirements within different sectors like medicine, automotive, and more.

While the NDE domain might not currently be featured in the roadmap, the fundamental concept of trustworthy AI has been defined, offering a useful framework for dealing with AI technologies. In addition, the roadmap is continually evolving, which suggests that AI for NDE may be included in the near future, as discussions progress and requirements become clearer.

1.2 Trustworthy AI

The concept of "Trustworthy AI" is at the core of NDE 4.0 and is closely related to established standards and it revolves around the fundamental question of how much we can rely on our NDE system. It's important to recognize that NDE itself doesn't change the reliability and functionality of a technical component or critical structure. Instead, it is often the primary means of obtaining information about their safe usage and performance. To achieve this, a functional quality management system as well as information on the trustworthiness of the NDE application, are essential. A failure in NDE doesn't directly lead to the failure of the component, but an unreliable testing system can result in unnecessary costs, and undetected potential threats may have to be addressed through design modifications or reductions in the component's lifetime.

For trustworthy NDE, the 2nd European American Workshop on the Reliability of NDT introduced the term "reliability." NDE reliability is defined as the extent to which an NDT system can effectively accomplish its objectives, regarding detection, characterization, and minimizing false alarms. This concept also led to the creation of the modular model (as shown in Fig. 1) of NDE, which includes intrinsic capability, application factors, human factors, organizational context, and the influential category of algorithms [3]. Within the subsection of algorithms, a variety of influences related to AI play a significant role, connecting reliable NDT to trustworthy AI.

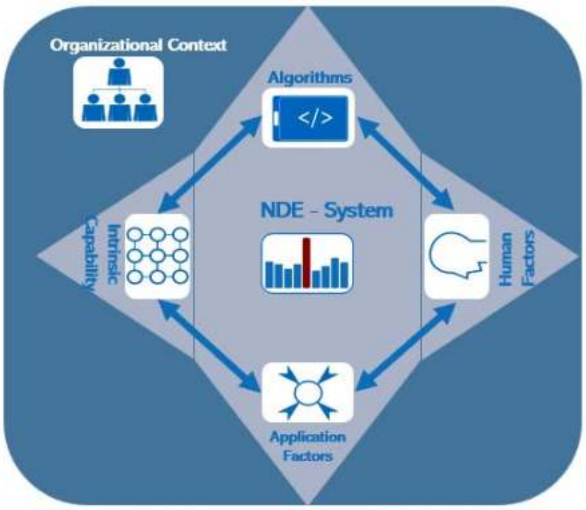

Fig.1 *Modular Model for the Reliability assessment for NDE*

Trustworthiness for AI is defined [4] by attributes such as fairness, autonomy and control, transparency, bias analysis, robustness, reliability [5], safety and security, as well as data protection. Here's how these attributes are relevant to NDE:

Fairness: Although fairness in the context of AI may not directly apply to NDE, it relates to the quality of data and coverage. Additionally, the collaboration with the human operator should be considered.

Level of Autonomy and Control: Current AI approaches aim to support human operators, who have the final say in testing system decisions. This Human-in-the-Loop approach enhances safety by requiring human confirmation, but it also places more emphasis on operator understanding of the method, raising concerns about issues like Automation Bias [6].

Transparency: NDE applications have an advantage in terms of transparency. Complex NDE applications often rely on the interaction between potential defects and fundamental physical testing knowledge to assess the testing system's capability. Metrics like the Probability of Detection offer transparent assessments of testing systems.

Bias Analysis: Evaluating the AI system for bias issues by examining how it performs across different demographic groups, materials, and defect types.

Robust Testing: Subjecting the AI system to a range of challenging conditions, including noisy data, variations in lighting or environmental factors, and difficult-to-detect defects, to assess its robustness.

Reliability: Evaluating the robustness of AI applications and estimating uncertainty, particularly the risk of making false decisions, is crucial for assessing reliability. In NDE, the Probability of Detection is a unique statistical metric used to assess reliability, especially in classification tasks where an incorrect prediction of the absence of a critical defect can have significant consequences, such as impacting railway service.

Safety and Security: While NDE AI applications don't directly cause physical harm to people, AI-based decisions can lead to unsafe conditions in the technical domain, akin to decision-making in medical diagnostics. The discussion of data security in NDE is unique and complex, often involving political considerations, due to the fact that the knowledge of testing results corporate secrets can be disclosed within NDE data.

In summary, ensuring trustworthy AI in NDE is a complex task, but it is essential to guarantee the reliability, safety, and security of critical infrastructure and technical components.

2 Reliability Assessment for AI in NDE

2.1 Reliability Assessment Concept for NDE

As previously mentioned, the typical metrics used to assess AI performance often involve Receiver Operating Characteristics (ROC), which include sensitivity and specificity, resulting in quantified characteristics like the Area under the Curve (AUC). Additional metrics such as the F1-Score are also commonly employed. However, all of these metrics overlook a significant difference between the use of AI in, for example, medicine and its use in NDE within maintenance programs.

In fields like medicine, even the slightest indication of a tumor is considered critical, but in context of the damage-tolerant concept in the technical field, certain defects, such as cracks, may not pose an immediate safety threat as long as they do not reach the critical crack size. Therefore, the size of potential critical defects is a crucial consideration in NDE. The question of when a testing system is capable enough to detect a signal resulting from the interaction of the defect, in relation to the defect's size, can be addressed through the Probability of Detection (POD).

The POD leverages the physical relationship of the testing method to describe its ability to detect defects. It takes potential interference into account which can introduce noise and data scattering, that may hinder defect detection. This relationship can be visually represented in the a (defect size) vs. â (signal response) graph (as shown in Fig. 2), which forms the basis for POD calculations, based on the decision threshold according to the distribution of the noise amplitudes, as depicted in Fig. 3.

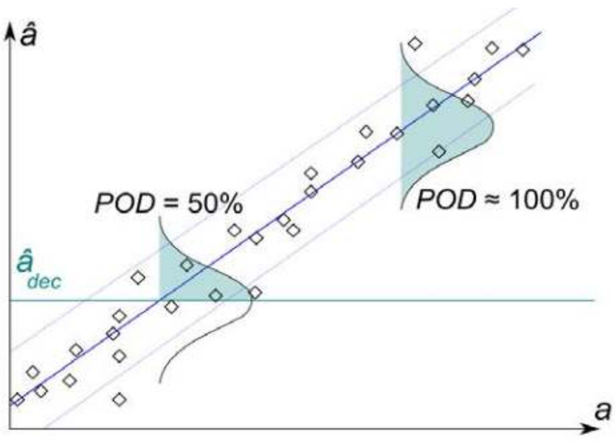

Fig.2 *â vs a graph for a POD evaluation*

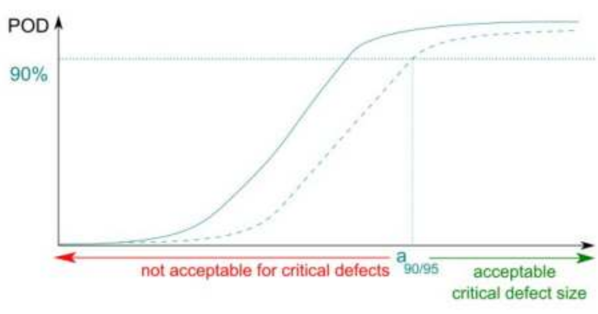

Fig.3 *POD graph an assessment of the NDT method*

The POD's ability to describe the physical relationship also contributes to the transparency aspect of AI performance assessment.

While the POD appears to be a suitable choice for evaluating AI in NDE, there are some aspects that warrant (a) discussion. As a statistical metric, the POD is effective under specific conditions and can be susceptible to misuse. Therefore, the demand for objectivity and potential third-party assessments, as stipulated in the AI-Act, is also applicable in this context. Organizations that offer objective assessments of NDE applications are limited. However, understanding how to establish and interpret PODs is essential, and fostering scientific discourse on these approaches within the community is necessary. Even though, POD assessments can be guided through various standards like MIL-HDBK 1823A, ASTM E3023/E2862, ENIQ Report no.41, etc. there are still many methods and techniques that are being used by several researchers. Many advanced methods like, multiparametric, model assisted POD methods, transfer function, etc. could not be easily implemented by individual organizations. Especially in the context of condition monitoring technologies, like structural health monitoring (SHM), NDE 4.0, etc., reliability assessments are extremely challenging. Hence, platforms for such discussions include the ICNDT Specialist International Group "NDT Reliability" and regular International Workshops on the Reliability of NDT/E.

2.2 Reliability Assessment Concept for AI

In assessing the specific AI process, it's essential to consider the well-established fact that the quality of data available for AI/Machine Learning (ML) algorithms, such as those utilized in the AIFRI project, is of paramount importance. As discussed in the preceding paragraphs, the Probability of Detection (POD) is a fitting metric for evaluating the use of AI in the field of NDE. As explained previous in Section 2.1, POD can be obtained based on the decision threshold applied to the signal response data. This decision threshold is, again, dependent on certain conditions on the distribution of noise amplitude data for a given false positive rate. Nonetheless, during the training phase of an AI system, it's crucial to remember that the unknown threshold established by the ML system, has a substantial impact on the system's detectability and false alarm rate.

For direct comparisons between different methods during the training phase, the general concepts of AI evaluation come into play. This means that the evaluation of an ML system for NDE is structured into two distinct phases. In the training phase, the ML system is assessed using Receiver Operating Characteristic (ROC) analysis to identify the optimal method based on factors like detectability and the false alarm rate (as shown in Fig. 4). In contrast, during the validation phase and the practical use (deployment) phase, the focus shifts towards evaluating the criticality of defects in terms of different metrics like size, area, volume, etc. As such, the ML system's performance is assessed using the POD, which aligns with its ability to accurately detect critical defects in real-world scenarios. This two-phase evaluation approach ensures that AI systems are both capable of detecting defects and reliable in practice.

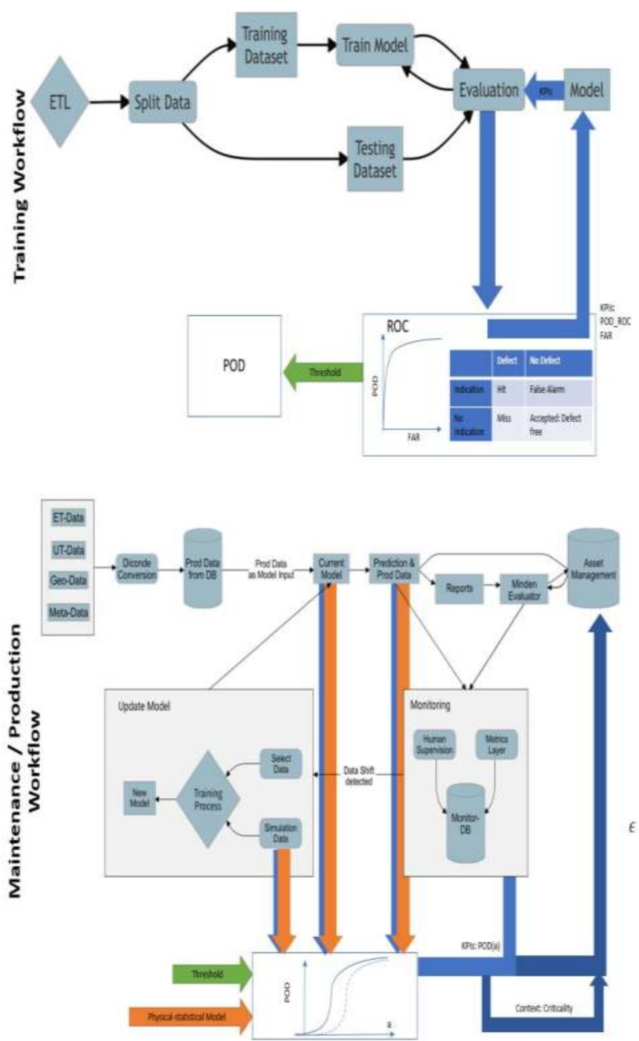

Fig.4 *Two-phase Data and Validation Concept with AIFRI: The Trainings Workflow and the Deployment Workflow*

3 MODEL DEVELOPMENT

3.1 Practical use of the AI evaluation in Railway

The state of railways in Germany is a critical topic, with implications for both sustainable travel and overall transportation quality. While it presents potential for eco-friendly travel across central Europe, the current quality of the transportation system is unsatisfactory. The high frequency of train delays, cancellations [7], and even derailments [8] indicates a need for significant improvement. It's worth noting that the costs associated with train derailments can be exorbitant, making it an imperative for infrastructure companies to ensure a safe and well-maintained rail network.

One of the complexities in the German rail system is its mixed use, with cargo, high-speed trains, and various other trains sharing a significant portion of the network. This variety in demands on rail applications needs a robust maintenance system to avoid unnecessary maintenance steps such as repairs or replacements. A key element in this context is the reliability knowledge derived from NDE techniques. The buzzword often heard in this context is "predictive maintenance." AI-driven NDE can facilitate predictive maintenance, extending the lifespan of critical assets, improving safety, and reducing downtime in railways due to maintenance activities. Apart from railways, the concept of predictive maintenance can multiply benefits to several industries, like aerospace, manufacturing and civil infrastructure.

Predictive maintenance is indeed an appealing concept, but its feasibility relies heavily on the reliability of the testing system. Without reliable data about probable defect size within the rails, without prioritizing and implementing predictive risk management strategies, the concept of predictive maintenance, becomes challenging.

One of the challenges stems from the fact that different stakeholders and engineering departments operate independently, causing a gap in efforts to combine all available information into a unified methodology. The AIFRI project endeavors to address this issue, aiming to gather information from various sources to tackle the future challenge of cost-effective rail maintenance and testing.

The testing process involves specialized testing trains that travel at high speeds over the rails, using Ultrasonic and Eddy current testing applications. The evaluation of the data is carried out separately, with decisions made about the need for further actions, such as detailed testing, speed restrictions, or section blockades. Within the evaluation phase, AI could potentially support human operators by expediting data analysis and improving its reliability.

Another issue is the limited number of testing trains responsible for the extensive rail grid in Germany. Currently, testing intervals are primarily determined by fixed time periods. However, there is a significant potential in shifting from fixed intervals to predictive variable time intervals. This transition must be highly accurate to ensure that critical rail sections are not left untested. Furthermore, due to outages of testing trains or the respective personnel, many scheduled test runs have to/had to be cancelled and must be rescheduled at short notice.

3.2 Evaluation results as the basis for planning test runs on railway tracks

The current scheme for scheduling rail test runs consists in fixed inspection intervals dependent on the maximum speed and ranges from four to 24 months. In this way, all track segments to be inspected, are classified into four different groups.

With the help of the results of the AI-based defect detection, a more individual and criticality-related approach can be derived. The POD analysis delivers an estimate of the size of small defects, which cannot be reliably detected by the testing system. The size corresponds to the $a_{90/95}$ threshold of the respective defect type, see Fig. 3.

Based on the information gathered in this project, an initial step involves classifying rail sections into different groups built on factors like the time since the last test, environmental influences, and testing train availability. Classification relies on mathematical approaches to plan the testing train routes and factors in the capability of the testing system in combination with the predicted behavior of potential defects within the rail.

For instance, considering a theoretical crack in the rail. Over time, this crack has the potential to grow due to the loads on the track and material behavior. The probabilistic nature of crack propagation behavior, combined with the probabilistic information about their detectability (POD), leads to a highly probabilistic situation. If the crack continues to grow without maintenance, it could lead to a catastrophic event before reaching the end of its life (EOL). Depending on the time and the potential for failure of a rail section, it's possible to calculate a metric that helps prioritize actions, a dimensionless quantity, in Fig. 5 called ε. This metric ε considers material parameters, load conditions, and the capabilities of the testing system, making it an ideal tool for planning testing train operations.

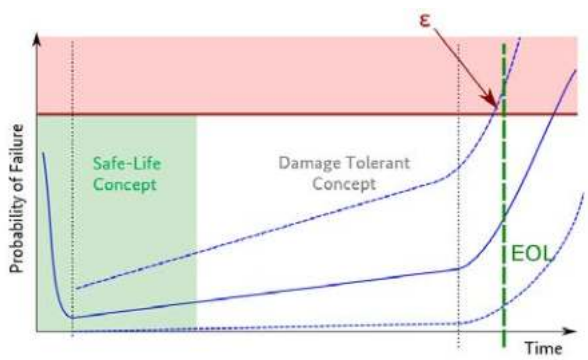

Fig.5 *Model for the Probability of Failure over time*

The initial value of the metric depends on the applicable extent of potentially non-detected defects. While no further maintenance is conducted on a specific rail segment, the metric increases according to the growth of the assumed non-detected defects. After a new test run, the metric is set back to the initial value, since present larger defects would have been detected by the testing system, see Fig. 6.

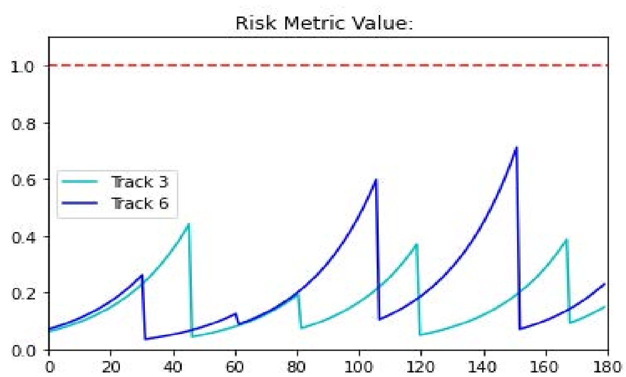

Fig.6 *Evolution of ε-values for two track segments over a horizon of 180 time periods with value set-backs at the times of track inspection*

In this way, an individual growth behavior of the criticality of each track, untested over a certain period of time, can be represented. These curve progressions, collected for all tracks of a network, input as objective parameters into a mathematical optimization model based on the models from literature [9,10]. While ensuring various planning constraints, combinatorial optimization can be used to address various objective criteria. Considering the ε-metric, minimizing the aggregated risk of all tracks at each time during a planning period (security aspect) or aiming to keep the curve values under a threshold by performing as few test-runs as possible (economic aspect). At the same time, the schedule should form the most efficient and possible rotation of the rail testing trains, for which personnel availability must also be considered.

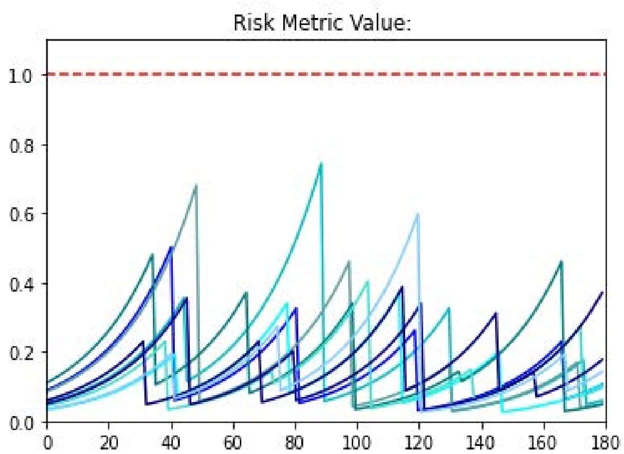

Fig.7 *Simulation of a regional network in eastern Germany with the objective of keeping the quadratic sum of the ε values of each track and time as low as possible for a planning window of 180 periods.*

4 RESULTS AND DISCUSSIONS

4.1 Reliability Framework

AI in NDE holds great promise for improving reliability, safety, and cost-effectiveness in various sectors. While AI has the potential to enhance NDE, it should be integrated thoughtfully and in conjunction with human expertise to mitigate these drawbacks and maintain the highest standards of safety and quality. Reliability assessment of AI plays an important role for improving safety and quality. Indeed, the Probability of Detection (POD) is a powerful and widely used tool with strong mathematical foundations for reliability assessments. It has been successfully customized for specific applications, even in high-reliability and safety-critical sectors, such as the nuclear industry and aviation. These approaches align well with the requirements set forth by the AI-Act and the Normungsroadmap.

4.2 Reliability data within AIFRI

A critical question remains for AI and NDE: What data do we need, and how much of it can we effectively use? While many AI applications have access to abundant data, even in the medical field, the technical component data, specifically those containing critical defects, can be quite scarce. This means that achieving trustworthy AI in NDE hinges on several factors, including the type of data, the extent of data coverage, and the overarching concept of "fairness" in data acquisition.

In the medical field, where vast amounts of data are available and some degree of comparability exists, NDE struggles to find relevant data on critical defects and achieve data comparability between components. However, in NDE, there is an opportunity to generate simulations or modeling tools as a data source for training and, to some extent, validation. Simulations allow for the creation of a substantial amount of data. Still, it is imperative to validate and benchmark this data to ensure that it accurately performs on real-world scenarios and is suitable for training AI systems effectively.

But first, the problem of imbalanced data in this research area has to be addressed. The majority of data are collected represents perfectly normal rail and simply taking all available measurements, could prevent the model from learning important patterns. The baseline for resampling training data is the number of artifacts that can be found in the measurements, which can be welds or drillings found in Ultrasonic data. From that information, it is possible to sample an appropriate amount of plain data to compose a meaningful data set suitable for training a model. The necessary amount of simulations is created with the same considerations in mind. All classification types need to be distributed evenly among each other to prevent the formation of biases.

In the future it is necessary for creating Deep Learning models with the help of simulation, the following questions has to be answered to prepare experiments and data for model validation and practical generalization. What should be learned that is in the data? With experts, artifacts and defects should be prioritized. Especially defects that are essential for the model to classify, e.g. cracks at drillings in 45° or 90° orientation, which will be simulated and serve as training data for the model. Hereby, we explicitly define and simulate which knowledge the model as to acquire. The next is designed to clarify the missing knowledge of the mentioned model. In reality, cracks are not necessarily limited to a 45° or 90° angle, but also might occur in between or outside of that range. In this case, cracks can be simulated with angles outside of the predefined range. They will not be part of the training data whatsoever and are solely considered during model evaluation. This way it is possible to examine how well the model can generalize and classify data outside of the explicit pattern it was trained on. Finally, it is to consider, whether the method introduced a possible bias towards simulated data and searched for patterns, that should not be mastered but that can occur in the data. Although the simulated data appears like truthful measurements, it cannot be ruled out that subtle differences are learned by the model. The models are not observable in the first place and cause a model bias towards simulated defects and fail with practically measured defects from the field. There is the need for specific artifacts, that are apparent in simulated data and field data alike. This enables to compare the model performance between both sources and evaluate further bias tendencies.

In summary, while data scarcity is a challenge in NDE, the ability to create simulations, offers a promising way to supplement this shortfall, but it also requires validation to ensure its applicability in real-world scenarios.

5 Conclusions

The AIFRI project is still ongoing, and it has achieved initial success in developing a model that interconnects various decision-making aspects within an objective decision-making process. The next phase of the project involves the following steps:

- **Development of the AI Technique:** The project will focus on further developing the AI technique, building upon the foundational work that has been accomplished.
- **Validating the AI Technique with Real Data:** To ensure the AI technique's effectiveness and reliability; it will be rigorously validated using real-world data. This step is crucial to demonstrate the AI model's practical applicability.
- **Development of a Train Planning Approach for a Specific Region in the German Rail Grid:** A specialized train planning approach will be created for a specific region within the extensive German Rail Grid. This region-specific approach will consider the unique requirements and characteristics of that area.
- **Discussion of Planning Results and Customization According to Non-Technical Requirements:** The project team will engage in discussions regarding the planning results and make necessary customizations to align the approach with non-technical requirements. These may include considerations related to regulations, policies, and other factors that influence decision-making beyond technical aspects.

These future steps will contribute to the project's ongoing efforts to enhance rail network maintenance and testing efficiency, ultimately improving the quality and safety of railway transportation in Germany.

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Adopting a Universal File Format for the Nondestructive Testing and Examination Industry

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Abstract

The NDT industry's transition to NDE 4.0 promises enhanced efficiency through digitalization, but it faces a significant bottleneck— the numerous incompatible file formats used by our equipment manufacturers. This article advocates the adoption of a universal open file format, namely, the .nde format. Utilizing HDF5 hardware description language, the .nde open file format offers increased data compatibility, accessibility, and archiving benefits, while its use of the JSON structure simplifies file management. In contrast to DICONDE, .nde proves flexible enough to generate DICONDE files, offering greater versatility.

The use of the open HDF5 language enables easy data viewing through multiple API options, facilitating customization to meet specific needs. Importantly, the .nde file format's autonomy from proprietary software enables independent auditors and regulators to use custom software for unbiased data validation.

The adoption of a universal open file format unlocks numerous possibilities for the NDT industry, including integration into digital twining and inspection data management systems, fostering cooperation and knowledge sharing. It also empowers the industry to harness the potential of artificial intelligence (AI). By standardizing data formats, collaborative AI development and data sharing among equipment manufacturers become feasible, making the AI integration process more efficient.

While the vision of industry-wide collaboration may seem ambitious, this article contends that the adoption of the .nde open file format is the logical next step in the industry's digitalization journey. Uniting key players to make all equipment compatible with .nde holds the promise of unleashing the industry's true potential and accelerating progress in the era of NDE 4.0.

1 Introduction

The NDT industry's constant quest for improved efficiency and our pursuit of the promises of NDE 4.0 are converging at a critical juncture. Our progress towards digitalization is being stunted, compared with other scientific industries, by our individualistic development model, which is epitomized by a prevalence of incompatible file formats. Pioneering the path forward necessitates an examination of the option to adopt a universal open file format, a measure enacted by other industries with desirable results. In this case, we'll present and scrutinize the potential of an open file format already in existence, namely the .nde format. Founded on the robust HDF5 architecture and utilizing JSON archiving, this technological amalgamation proposes a novel dimension of data accessibility, preservation, and interoperability, desirable aspects that should compel industry stakeholders to consider its implementation.

2 NDE Universal Open File Format, a Panacea for Stunted Progress

Throughout decades of NDT technological evolution, we've witnessed a proliferation of proprietary software, typically accompanied by a distinct and proprietary file format. Even within one manufacturer's product line, file format variation has been known to occur. The repercussions of this widespread incompatibility resonate throughout the industry, creating frustrating hurdles that prevent or complicate data sharing between collaborators, auditors, and experts. This discrepancy also hinders customization, particularly when dealing with diverse inspection technologies and instruments. The consequence is a fragmented NDT landscape that demands a unifying solution.

As an open file format, .nde offers a remedy that can satisfy the needs of all stakeholders. Constructed on a base of HDF5, a durable and accepted archiving solution, .nde transcends file size limitations and fosters data management, storage, and retrieval efficacy. Furthermore, the format's flexibility ensures that data accessibility is not confined to proprietary software. Since it's not proprietary and can be read without a proprietary application programming interface (API), the .nde file format could be universal in its compatibility, agnostic to equipment origin, and adaptable to user needs. However, this universality is dependent upon its acceptance and wide implementation within the industry.

3 Key Advantages of the NDE (.nde) Open File Format

The .nde format's use of the HDF5 architecture translates into robust compatibility across diverse computational platforms and programming languages, helping ensure its longevity. A notable benchmark of its acceptance, the HDF5 format has been integrated into numerous projects undertaken by the National Institute of Standards and Technology (NIST), a key industry standard authority. In a similar vein, the .nde format's use of JSON to embed file parameters not only enhances its file management efficiency, but also aligns it with U.S. National Archives and Records Administration (NARA)'s accepted standards.

Another contender, established NDT archiving and imaging standard DICONDE, has proven sufficient for simpler data. However, DICONDE format lacks robustness when faced with the complex data acquired and recorded by methods such as ultrasonic testing (UT) or eddy current testing (ECT). The .nde format rises to the occasion by accommodating diverse and intricate NDT data requirements, underscoring its adaptability.

Being HDF5-based, the .nde format offers an array of customizable options for data visualization, either using official open-source APIs or various user-interface alternatives that can be tailored to specific requirements. Of particular significance is the absence of proprietary software, which empowers independent auditors and regulators to employ custom solutions for objective data validation, fostering impartial review processes.

The integration of a universal open file format into the NDT community has the potential to usher in a new era of cooperation and innovation. Beyond overcoming interoperability challenges, .nde proposes a future where conventions, references, and code snippets are readily shared among stakeholders. Furthermore, the stage is set for the infusion of artificial intelligence (AI) into NDT practices, with a standardized data format simplifying data sharing and accelerating the development of AI-driven solutions.

4 Conclusion

The NDT industry is poised for a major leap forward in our digital transformation through the adoption of the .nde open file format as a universal file format. This endeavor necessitates industry-wide alignment, wherein all key players commit to enabling their equipment for .nde compatibility. The parallel of other industries that have standardized their file formats underscores the urgency and rationale behind this pivotal evolution. By casting off the shackles of file format incompatibility, the NDT industry stands to unlock its full potential, accelerating progress in the era of NDE 4.0.

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CorrosionRADAR for Remote Monitoring of Corrosion Under Insulation (CUI) with Industrial IOT

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Abstract

This paper explores the utilization of digital technologies, specifically the Industrial Internet of Things (IIOT), in the context of predictive Corrosion Management, focusing on a compelling case of corrosion occurring under insulation. It discusses the implementation of digitalization tools and presents real-world examples of their application in the field. By harnessing digital data collection and predictive algorithms based on factors like moisture levels and temperature, hidden corrosion issues such as Corrosion Under Insulation (CUI) can be effectively managed.

This approach involves leveraging gathered data to comprehensively oversee assets, identify high-risk areas, and plan inspections and maintenance proactively. The paper outlines a predictive methodology enabling asset owners to manage their assets both economically and safely by identifying and addressing risks beforehand. This technology integrates sensors to assess conditions under insulation and employs predictive modeling to swiftly estimate potential risks.

The paper delves into various use-cases and practical applications, demonstrating how employing sensors and industrial IoT can revolutionize the detection and prediction of corrosion in the field. This advancement holds significant promise for ensuring the integrity of assets plagued by concealed corrosion issues like CUI. The paper also presents the latest field case studies, bolstering confidence in this monitoring approach and contributing to the ongoing development of knowledge within the corrosion industry.

Keywords: *Corrosion Under Insulation, CUI, Remote monitoring, Industrial IOT*

1 Introduction

Based on analysis by AMPP the corrosion costs countries approximately 4.2% of their Gross National Product (GNP) on average. In the United States, this figure rises to around 6% of GNP. Corrosion costs can be categorized as direct or indirect. Direct costs involve equipment failure, repair, and maintenance, while indirect costs encompass production losses. For instance, in a gas sweetening plant, the production loss due to corrosion in just one unit equals 47% of the unit's annual direct corrosion costs. Production losses can occur due to scheduled turnarounds, inspections, or worse, unplanned shutdowns resulting from corrosion failures.

Corrosion under insulation (CUI) is a significant concern in industrial plants as insulation is applied for various reasons, such as heat conservation, cold conservation, thermal protection, process stabilization, and winterizing. Additionally, insulation is used for sound control, condensation control, freeze protection (e.g., heat tracing), and fire protection. Erickson et al. identified around 175,000 vulnerable locations in above-ground pipelines on the North Slope of Alaska susceptible to CUI. CUI often remains undetected for extended periods and is only discovered when insulation and cladding are removed. The corrosion rate of carbon steel under insulation can be 20 times higher than in normal conditions, making CUI particularly challenging.

Current guidelines advise against unnecessary insulation application and propose alternatives like screens or protection bars due to the high corrosion rates under insulation. The widespread use of insulation on equipment below 150°C became common during the 1970s when petroleum costs were high. CUI also poses challenges in cryogenic services, where assets are insulated, and water condensation is possible. It affects liquid storage tanks and intermittent cryogenic transmission piping.

Given the economic impact, insidious nature, and mitigation efforts involved, CUI is a crucial topic in asset integrity and corrosion management. This article delves into the significance of CUI as one of the most challenging types of corrosion to predict and mitigate. It explores the use of Industrial Internet of Things (IIOT) technology in mitigating CUI in cold service equipment and presents a real-world field application case.

2 Corrosion Under Insulation Management Practices

2.1 CUI Risk Management

CUI is a challenge to the industry, and plants try to tackle it in many ways ranging from strict measures such as full removal of insulation, to minimal inspection accompanied by oftentimes ineffective NDT methods. This underpins the lack of a systematic approach to CUI management [7].

All the strategies in asset integrity management are founded on plan, do, check, and act (PDCA) approach. At the planning stage the parameters leading to the risk of equipment or piping are established and risk values are assessed.

In the next stage, the risk mitigation activities including the inspections are performed. Then, it is verified that the current risk mitigation activities are sufficient or require improvement. Next, the achieved results are used to update the strategy, and standardization and procedure development. This cycle goes on leading to constant improvement of the system.

A presentation of the PDCA cycle for CUI is given in Fig.1.

Fig.1 *Corrosion under insulation plan-do-check-act approach to achieve asset integrity [7]*

2.2 CUI Risk Based Inspection

With regards to CUI Risk assessment, API 581 and DNVGL RP-G109 have taken two different approaches. API 581 considers CUI as a form of thinning (in case of ferritic CUI) and Chloride SCC (in case of austenitic CUI) and applied similar approaches for damage factor calculations on them which will be discussed further below while DNVGL considers CUI situation as a form of failure for which different barriers must fail before it happens.

It is worth noting that both methodologies use the same concept of risk as the multiplication of probability of failure and consequence of failure as shown in Risk = Probability of Failure (PoF) X Consequence of Failure (CoF) Eq. 1 . Not much can be done to reduce the consequence of failure as it is well rooted into plant's operational and design conditions. However, PoF can be reduced effectively leading into risk reduction.

Risk = Probability of Failure (PoF) X Consequence of Failure (CoF) Eq. 1

2.3 CUI Monitoring

There are different approaches to monitoring of CUI. Each approach might use one or a combination of physical properties to monitor CUI progress. These include the electrical resistance, ultrasonic waves reflection by water, change in capacitance or electromagnetism with moisture presence, and measurement of electrochemical impedance of the degraded coatings [8].

Commercially available sensors for CUI monitoring and the parameters they use to detect CUI are listed below:

1. Indirect CUI measurement by sacrificial wire
2. Wall thickness measurement
3. Water accumulation
4. Moisture/humidity
5. Spot sensors
6. Electrical capacitance
7. Electromagnetic waves
8. Coating degradation
9. Fiber optics

The monitoring devices available in the market usually try to detect moisture under the insulation to monitor the conditions leading to the CUI. Also, the monitoring techniques use sacrificial sensors which can send signal when the environment is conducive to corrosion.

2.4 Industrial Internet of Things

The industrial internet of things (IIoT) is the use of smart sensors and actuators to enhance manufacturing and industrial processes. Also known to enable Industry 4.0, IIoT uses the power of smart equipment and real-time analytics to take advantage of the data. Connected sensors and actuators enable companies to pick up on inefficiencies and problems sooner and save time and money, while supporting business intelligence efforts.

In manufacturing, specifically, IIoT holds great potential for quality control, sustainable and green practices, and overall supply chain efficiency. In an industrial setting, IIoT is key to processes such as Predictive Maintenance (PdM), for condition-based maintenance in asset integrity management. Corrosion risk management have emerged as an attractive use case of remote monitoring enabled by IIOT technologies.

The core components of IIOT technology are:

- Connected devices that can sense, communicate and store information
- Data communications infrastructure including wireless networks
- Storage for the data that is generated by the IIoT devices
- Analytics and applications that generate insights from raw data
- Dashboard applications for decision making

3 Use Cases and Applications

3.1 Cold Service CUI cases

There are some characteristics in certain processes and operating conditions that make equipment generically prone to the CUI. Previous histories of failure are reported in the literature for molecular sieve dryers [9] and fractionation refrigerators demonstrate that cold temperature services can suffer from CUI, no matter the design measures taken to mitigate it. Even the use of resistant but costly coatings such as thermal sprayed aluminum (TSA) might not alleviate the problem.

3.1.1 Constant Cold Service

Equipment operating in cold service range such as chilling equipment and refrigerants (Fig.2) are usually assessed with lower corrosion rates in risk models, or even as immune. This is due to the common understanding that corrosion rate is low at zero or sub-zero temperatures. However, the failures that have occurred in the industry undermine this supposition.

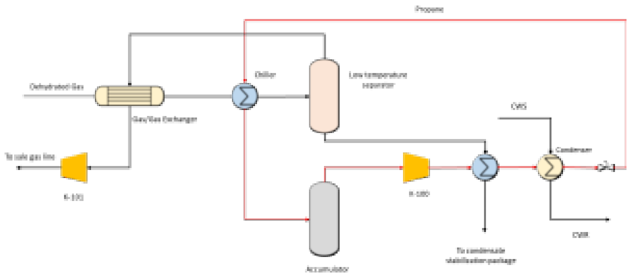

Fig. 2 *Process flow diagram of propane refrigeration system for condensate separation. The propane loop is the refrigeration loop [10].*

Equipment working at low temperatures is usually protected through vapor barrier coatings. This additional design requirement adds to the complexity and risk in comparison to their hot temperature counterparts. There are cases of severe CUI observed in fractionation units where the protection by vapor barrier is lost and water has condensed on the surface.

The requirement to keep cold service equipment isolated to avoid water ingress and condensation under the insulation due to low temperature, makes the condition for their inspection more complex. Bear in mind that replacing insulation with metal cages or use of inspection windows as it is common for some hot insulations are ruled out for cold insulations. The plant management has no option but to inspect them fully either by non-intrusive techniques or by complete delagging during shutdowns [11].

Therefore, counterintuitively, operating under cold service, or having parts or sections of the system operating in this temperature range, can increase the CUI risk compared to hot service.

3.1.2 Cyclic Cold Operating Temperatures

Cyclic operating temperature can also exacerbate the CUI situation for cold temperature services. Constantly operating at sub-zero temperatures may only cause CUI to occur at hot fingers (areas where the temperature allows the formation of water), but in the case of cyclic operation, liquid water may form underneath the insulation.

One such example is the molecular sieve dryer and piping (e.g. in ethylene plant). Fig 3 shows a failure that occurred in this cold service process.

1. The dryer passes through three stages of operation:
2. Cold temperature when in drying mode (30 bar, -17oC)
3. High temperature in the regeneration mode (4 bar, 220oC)

Ambient temperature in the cooling mode

There are usually two dryers in the unit. When one is in service, the other dryer is in regeneration mode. In this case, the wet fluid enters the dryer which is in operation at cold temperature and the water is adsorbed on the molecular sieve resins.

In regeneration mode, however, the inlet valve is closed and now the hot stream is passed through the molecular sieve resins from the outlet. Finally, to put the dryer back to service, it should be cooled down at ambient temperature.

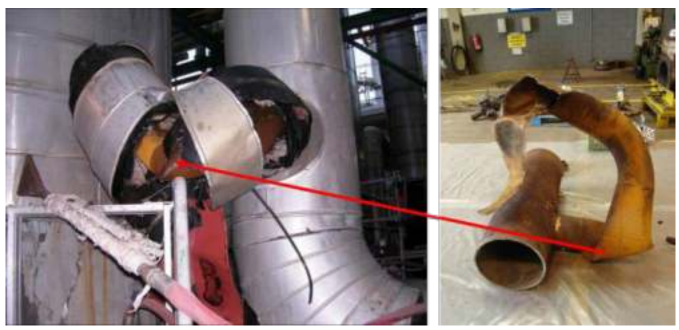

Fig 3 *Failure of a carbon steel regeneration line to a cracked gas dryer of an ethylene plant [12]*

This cyclic service temperature produces a range of micro-environments below the insulation, which can lead to severe corrosion and failure. Additionally, all the piping and equipment in such service conditions are susceptible. Only by stringent and expensive measures, such as full delagging of the insulation, can the CUI risk be controlled.

3.1.3 Cold Service Transfer Lines

Product transfer lines for liquefied petroleum gas (LPG) are another case where low service temperature can increase the CUI risk. These transfer lines are usually long insulated pipelines that stretch from the storage tanks to the loading and unloading sites or platforms. The criticality of these pipelines from business and safety aspects makes the site operators think twice when they want to conduct CUI inspections on them.

Similarly, the variations in temperature when the fluid is transported through the pipelines is one source of the risk. Their length also complicates the situation as proper design should be maintained along the pipeline route.

3.2 Gas Fractionation Columns

Low boiling point gas fractionation columns experience a temperature gradient from bottom to top. The reboiler and the reflux usually operate outside the susceptibility range for the CUI; the former above the susceptibility range and the latter below. However, areas close to the top of the columns might experience temperatures within the susceptibility range. Operational changes in the feed might also affect this operating temperature.

Difficulty in accessing to column tops, and cumbersome logistical preparations to create access to these areas, make inspections the last option for plant managers. However, there are industrial reports that CUI is a serious damage in those areas.

3.2 CUI Monitoring with CorrosionRADAR

CorrosionRADAR (CR) is a technology developed and patented to address the industrial demand for remote monitoring of Corrosion Under Insulation (CUI). It stands out as the longest-serving product in the realm of CUI monitoring. The technology relies on the Guided-wave electromagnetic principle and incorporates sensors within insulation. These CR sensors function as moisture and corrosion sensors, connected to a node that transmits data to a cloud-based repository. Designed to withstand complex field conditions like flanges, bends, and pipe supports, these sensors can carry an electromagnetic wave effectively.

It operates using permanently installed flexible long-range sensors placed on the outer surface of pipes, eliminating the need for inspection scaffolding. These sensors comprise a moisture sensor and a sacrificial corrosion sensor made of carbon steel. The moisture sensor, consisting of a pair of wires, detects moisture beneath the insulation. Both types of sensors are connected to channels on a node, which send and receive signals. Each sensor, when set up individually, can cover a length of 100 meters on the asset. The gathered data is sent to the cloud and analyzed, enabling risk assessments on the system dashboard.

CorrosionRADAR has demonstrated promising results in previous applications on cold service assets. The sensors provide real-time data on moisture ingress inside cold insulation, which is costly to address. The presence of moisture barriers in cold applications further complicates the situation. The system's installation on a cold service dryer revealed dynamic changes in risk values upon moisture detection, even when traditional Risk-Based Inspection (RBI) systems indicated low corrosion rates and recommended delayed inspection plans. By integrating the RBI system with digital monitoring, the inspection team could take immediate action upon detecting moisture within the insulation, preventing undetected failures Fig 4.

Live data from moisture and corrosivity sensors are transmitted in real-time to a cloud system, where they undergo processing. The asset's dynamic risk is calculated based on industry standards such as DNV-RP-G109 and API 581 to update risk values. An example of this integration is depicted in Figure 5, showcasing the increase in Water Probability of Failure (PoF) and Material PoF according to DNV-RP-G109 after moisture detection.

Fig 4 *CorrosionRADAR CUI monitoring system and different arrangements of the sensor appropriate for different piping or vessel types as well as the node that is capable of sending the data to the cloud.*

***Fig 5** Risk dashboard connected to CUI moisture and corrosivity sensors*

This continuous risk assessment approach kept the site's inspection and maintenance team alert to any changes in CUI conditions. By responding promptly, they were able to mitigate failures that might have gone unnoticed if only a traditional risk-based inspection methodology had been employed.

4 Summary

Analyzing past failures within the industry context reveals that specific equipment and processes operating under cold service conditions are inherently susceptible to Corrosion Under Insulation (CUI). This heightened vulnerability stems from active damage mechanisms linked to the service processes. Moreover, the risk associated with insulated cold service equipment might be underestimated when using Risk-Based Inspection (RBI) methodologies.

The authors argue that implementing Condition Monitoring through the Industrial Internet of Things (IIOT) can supply essential information to mitigate the risks inherent in cold service conditions, reducing the likelihood of CUI failures or damage. Solely relying on risk-based inspection methods carries the danger of underestimating corrosion rates in cold service CUI scenarios. With CUI condition monitoring, inspection teams can update risk values in real-time, enabling swift decision-making.

Furthermore, remote condition monitoring enhances data reliability. This provides the inspection and maintenance team with ample lead time to take proactive measures, preventing unexpected failures from occurring.

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DPAI: In-situ process intelligence using Data-driven simulation-assisted-Physics aware AI (DPAI) for Simulating Wave Dynamics

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Abstract

AI models such as convolutional long short-term memory (ConvLSTM) recurrent neural network (RNN) have been shown here to have the capability to simulate ultrasonic wave propagation in the 2-D domain. This DPAI approach uses the Data-driven but simulation-assisted-Physics aware approach to utilizing **AI** networks. Our DPAI model comprises ConvLSTM with an encoder-decoder structure, which learns a representation of spatio-temporal features from the input sequence datasets. The DPAI model is trained with finite element (FE) time-domain simulation datasets consisting of distributed single and multi-point source excitation in the medium, reflection from the simple boundaries, and phased array steering. Here, this approach, called the DPAI model, is demonstrated for modelling multiple point sources to simulate forward wave propagation, reflection from the boundaries, and phased array beam steering ultrasound wave dynamics in a 2D plane. The trained DPAI model was found to be significantly faster in generating simulations for the time evolution of field values in the elastodynamic problem when compared to the conventional finite element explicit dynamic solvers.

Keywords: *DPAI, Ultrasonic Wave simulation, Phased Array, FE, Deep Learning, RNN, ConvLSTM.*

1 Introduction

Ultrasonic wave propagation has wide-ranging applications in several fields, such as geological investigations, seismic research, non-destructive evaluation [1], and biomedical imaging. Improving our comprehension of the physics behind these applications depends heavily on the numerical modelling of ultrasonic wave propagation. The transitory nature of wave propagation and the three-dimensional region in which the wave is to be modelled result in enormous processing resources and calculation times, which restricts the use of modelling in real-time field inspection. Numerical models such as Finite Element [1-2], Finite Difference [2], Finite Integrals [3], Galerkin Meshless [4], and other comparable techniques have been employed for modelling wave propagation simulations. The adoption of Graphical Processing Units (GPUs) with parallel computing models for wave propagation [5-6] and several other advancements in mesh discretization and computation have resulted in these techniques that are quicker and need less processing power.

The FE simulation is, nonetheless, widely used for simulating ultrasonic simulations out of all numerical techniques [7]. By solving the wave equation's partial differential equation with specified boundary conditions, the FE simulation offers precise solutions for the most complex problems involved in solving wave dynamics for various geometry and boundary conditions. However, as the number of FE elements/nodes increases, it is generally known to be computationally costly, especially for realistic problems such as higher inspection frequency ranges and larger geometrical domains [8]. Due to its high memory requirements, it is mainly utilized for experimental validation or to create a proof of concept for the ultimate design iteration. An alternate strategy is to create a data-driven solution for wave propagation modeling by extracting the physics from numerical simulation datasets [9-10].

Larger training datasets becoming available, algorithm advancements, and exponential increases in processing power have all contributed to an unprecedented rise in interest in deep learning algorithms in recent years. Massive amounts of input data, particularly high-dimensional datasets [12], could be effectively classified [13], regressed [14-15], clustered [16], or have their dimensionality reduced using deep learning algorithms. Therefore, one of these deep learning models could be used to generate wave propagation, depending on the structure of the datasets being available [17-19]. Since these training datasets include both temporal and spatial characteristics, recurrent neural network (RNN)-based techniques are thought to be the best for simulating the propagation of ultrasonic waves [20-21]. Contemporary deep learning systems like long short-term memory (LSTM), a specific kind of RNN structure employed for diverse applications in science and engineering, can handle vanishing gradients and create long-range temporal representations due to their inherent capacity [22-23]. Convolutional LSTM (ConvLSTM) might be utilized instead of this algorithm as it is less successful at extracting spatial information from the training dataset. In order to complement the temporal state with spatial information, the convolutional operation is used inside the LSTM cell [24-27].

In this work, we present a novel methodology for developing a hybrid Data-driven-Physics-based AI (DPAI) model for simulating ultrasonic wave propagation in real-time. This involves a supervised learning model obtained from deep convolutional long short-term memory (ConvLSTM) networks [28-30]. Our earlier research demonstrates the modeling of wave reflection from boundaries with varying physical settings and forward wave propagation simulation [31]. Additionally, in order to simulate phased array beam steering wave simulation in a 2D domain, the authors wish to expand the DPAI model widely. This study presents the development of three distinct DPAI models. The training datasets for the first DPAI model are created by simulating the time domain FE simulation of multiple point excitation sources inside the solid medium of forward wave propagations. This model is then utilized to model different multiple-point source excitation simulations. Similar to the first DPAI model, the second one is trained using a collection of FE ultrasound wave simulations, which provide the training data for single-point excitation at the medium's top surface with different 2D geometrical shapes. The phased array (PA) ultrasound technique is the most extended for defect detection and characterization in the NDE domain because of the ability to focus and steer the beam without the physical movement of the transducer. The primary advantage of the PA technique over the conventional ultrasonic technique is that large regions can be inspected from a single location using various ultrasonic profiles such as plane wave and beam steering and focusing without disturbing the transducer position, which is a much faster process. Therefore, we have modeled the 16 active elements phased array probe with variable angles of -40 to 70 degrees in FE to produce the training dataset for the third DPAI model. In order to extract the temporal evolution and spatial feature information of ultrasonic wave mechanics, the DPAI network design uses a convolutional LSTM encoder-decoder structure.

Using this DPAI model, it is shown to be feasible to model simulation with significantly reduced time and resources for computation that compares well with the FE model outputs. Furthermore, the DPAI, like most data-driven models, is based on algebraic calculations, and the computational resource requirements are significantly reduced compared to conventional numerical approaches.

This paper is organized as follows: Section 2 describes the DPAI training datasets created using Finite Element Analysis. The formulation of the wave propagation problem using the DPAI algorithms is detailed in Section 3. Numerical experimentation and results are given in Section 4, and Section 5 concludes the work.

2 Simulation-Assisted Training Data Set Generation for DPAI:

The AI model learns the principles of ultrasonic wave propagation while it trains the network to produce real-time simulations. This work uses the FE simulation method to obtain the bulk datasets needed for training the DPAI. This section provides a detailed description of the generation of the simulation-assisted data collection.

2.1 Finite Element Modelling for Transient Wave Dynamics in the 2D domain:

Large amounts of simulated-assisted data are required for the AI-enabled wave propagation in solids, and these are created by modelling FE simulation in the time domain. Abaqus/Explicit Dynamics Solver, an FE software package, is used to solve the physics-based wave equation. A comparable 2D plane strain CAD model is created using a 35 x 35 x 20 mm test sample of carbon steel. The bilinear quadrilateral element is used to discretize the 2D domain into 22 elements per wavelength (longitudinal wave velocity). The FE nodes function as transmitter-receiver pairs by establishing a standard ultrasonic transducer location. To avoid the undesired reflections from ends, ALID (absorbing layers using increasing damping) applies the absorbing boundary conditions on all sides of the plate [32]. The two-cycle Hanning windowed tone burst signal of 5 MHz inspection frequency is used to excite the ultrasonic pulse of an incident wave given in function of time. The pulse excitation is applied in terms of single/multiple concentrated forces on nodes that act as the physical transducer. Figure 2(a) reports the three excitation point sources in the FE model. The sequence of the displacement plot over the total simulation time is extracted for every successful completion of the analysis. A similar approach is followed from our prior work for modeling [27].

In this work, we aim to teach DPAI the physics of wave propagation by creating different 2D CAD models based on the probability distribution function (PDF) by computing critical transducer position parameters to generate a bulk quantity of training simulation data sets. The critical transducer position parameters are calculated using PDF based on the influence of real-time experimentation, such as expected loading direction, position probabilities, number of excitations point sources, the sensitivity of instruments, etc. We have generated three different datasets to develop three different DPAI models. In the first type of dataset, a one-direction load is applied per simulation in terms of concentrated force either in the X or Y-direction in the FE modelling, which is randomly located in the test sample area. The excitation point source is distributed from single to five excitation point sources. A total of 500 FE simulation sequences of the frame dataset are created.

In the second type of dataset generation, we modelled three distinct geometrical CAD models with physical dimensions of 40 x 40 mm overall. Excitation load is applied to the top-edge nodes of 1000 CAD models, each with three distinct form domains, as shown in *Figure 5(a)-(c).* These models are then solved in FE simulation. All other CAD model surfaces have traction-free boundary conditions applied to them in order to permit reflections off the side and rear walls.

The third generation of datasets involves solving the governing wave equations in FE using initial and boundary conditions of the phased array of active elements. Using a predetermined focal law that has been computed for beam steering, the 16-element active aperture in the PAUT approach is activated. These delay laws are fed into the Abaqus to model the concentrated force as the emitting source in the medium. All the active aperture elements are triggered in parallel using pre-defined delay laws to form the ultrasound beamforming to steer in the medium, and the FE simulation snapshot is shown in *Figure 7(a)*. A total of 600 FE simulations is created by applying the delay laws of each beam steering angle. The steering angle used for simulation lies between -40 degrees to 70 degrees.

Generating one FE simulation takes 40 minutes using time-domain FE analysis executed using a Dual Intel Xeon Platinum 8168 processor with 48 cores and 1000 GB RAM. Hence, this conventional explicit dynamics FE analysis is time-consuming for design iteration. We have introduced the DPAI network to generate synthetic wave dynamic simulations to overcome this.

3 Modelling Wave Propagation Simulation using DPAI

In the Deep Machine Learning framework domain, recurrent neural networks have played a vital role in modeling spatio-temporal sequence output. The DPAI model architecture used for modeling wave propagation simulation is discussed in detail in the following section.

The LSTM is a unique RNN structure modeled for addressing vanishing gradients and learning long-range dependencies. The LSTM shown in *Figure 1(b)* consists of the following elements: a memory cell C_t, which can accumulate and forget the state being tackled from time-step to time-step. The input gate i_t controls the weather to include new information in the memory cell. The forget gate f_t is responsible for removing information from the cell state, and an output gate O_t is responsible for transferring information from C_t to hidden state H_t. The hidden states could retain the memory of past knowledge and learn the long-range dependencies in sequence data. The LSTM network is successful in many domains, but it will be a poor choice for modeling wave propagation problems, which is overcome by implementing a convolutional LSTM network. In this network, the higher dimension matrix multiplications are replaced with the convolutional operation, which reduces the number of training parameters and maintains the spatial features intact [24]. The key equations for the ConvLSTM network are as follows from our prior work [28].

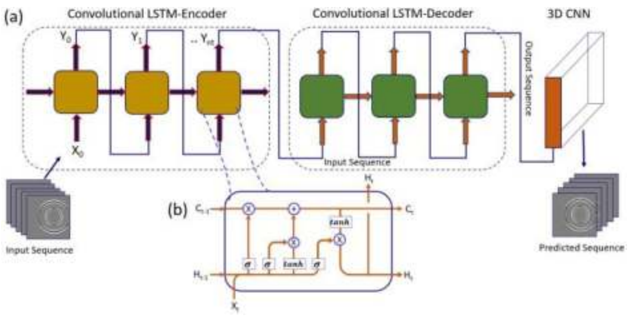


***Figure 1: (a)** Typically DPAI stacked convolutional LSTM encoder-decoder architecture for modelling wave propagation phenomenon. (b) Structure of a single convolutional LSTM cell.*

The DPAI network algorithm is a combination of a convolutional neural network (CNN) and a recurrent neural network (RNN). We have used the proposed DPAI network for our spatial-temporal sequence generation problem, as shown in *Figure 1(a)*, consisting of an encoder and a decoder network containing two convolutional LSTM cells stacked together. Each input sequence is fed into a new encoder ConvLSTM cell together with the hidden state from the previous ConvLSTM cell. The encoder processes input iteratively through various ConvLSTM cells and outputs embedding tensor, representing wave propagation. The output of the encoder-embedded tensor is fed to the decoder network to produce a predicted wave propagation simulation. The decoder cell outputs the sequence of feature maps for each predicted frame. These feature maps are transformed into actual predictions using 3D CNN layers with a sigmoid activation function.

4 Numerical Experimentation and Results using the DPAI model

In the following section, ultrasonic wave propagation physics is taught to the DPAI model while training the network to generate the synthetic elastodynamic simulations is discussed in detail. The DPAI architecture is implemented based on the dataset generated in section 2. The qualitative and quantitative results of trained three different DPAI model performances on wave propagation datasets are described in detail in this section.

4.1 DPAI model training and testing on forward wave propagation simulation:

To train the artificial intelligence algorithms needs a large number of training data sets for better performance. The proposed DPAI model is trained using FE-generated simulation-assisted training sequences created using a single excitation to multiple point excitation sources applied as triggering signal pulse. These training data sets are extracted from FE simulation as the sequence of images over 5 microseconds with a sampling time interval of 0.74 microseconds per frame. These simulation data are extracted as frames over 5 microseconds with an interval of 0.74 microseconds per frame. We have created a total of 1000 simulation data sets from FE analysis. These sequences contain 675 frames per simulation. Each simulation is divided into a mini-batch of 12, and each mini-batch contains 15 sequences of frames. The total mini-batch is split as 80% for training, and the remaining 20% is used for testing. Each sequence of frames is further divided into 10 for the input and 5 for the ground truth. Although the input sequence and ground truth instances are sliced from the same simulation having dependencies, this splitting strategy is still reasonable because, in real experimentation, we have access to the previous and successive subsequent frames, which allows us to predict the full-length simulations. These datasets are in greyscale with pixel values of range [0, 255], normalized from [0,1] pixel values with a size 256 x 256.

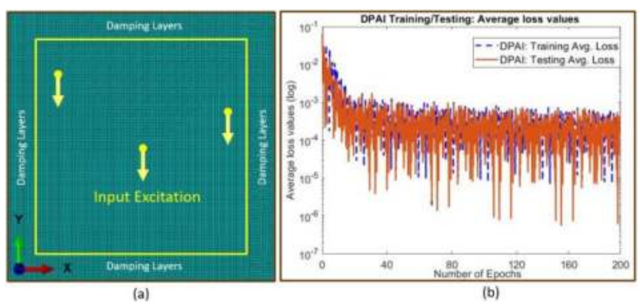


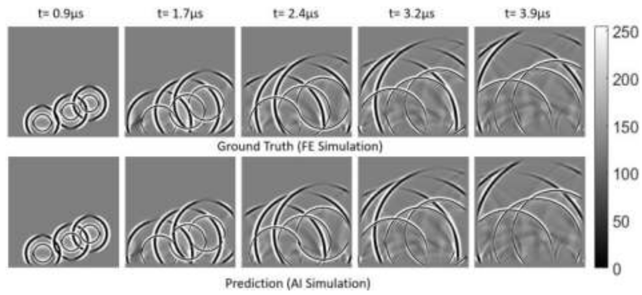
***Figure 2: (a)** An example of the FE model, where the incident wave is triggered by modelling the three excitation point sources. The absorbing boundary condition is applied to all wall sides with different damping coefficients to prevent undesirable effects. **(b)** DPAI: Training/Testing: the forward wave propagation dataset's average loss values over the number of epochs.*

The proposed DPAI model is implemented in PyTorch-lightning [33-34], an open-source framework that is great for removing many boilerplate codes and integrating multi-GPU training. The DPAI architecture shown in Fig. 2 consists of four layers of encoder-decoder structures stacked together. Each layer contains 256 hidden states with a 5 x 5 kernel size. A mini-batch size of 12 sequences is drawn from a random distribution as input to the network. The DPAI network is trained to minimize the Mean Square Error (MSE) loss function using the back-propagation through time (BPTT) algorithm. The network's learnable hyperparameters are initialized to zeros to prevent the instability of the network. The Adam optimizer is used to optimize different network weights and biases with a learning rate set to 0.0001 and trained for 200 epochs.

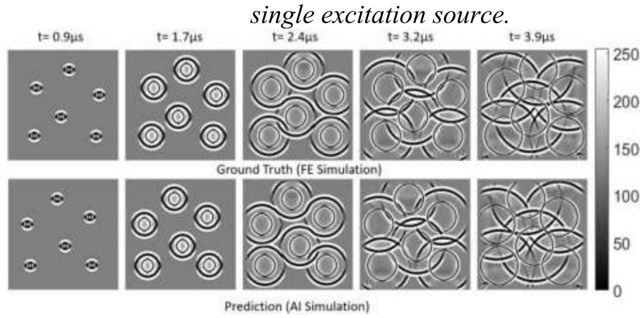
The average loss metric is used to measure the performance of the network while training. The loss is calculated by comparing the network-predicted simulation with ground truth simulations. *Figure 2* shows the average loss values over the number of iterations. The average loss values are stabilized over the iterations; thus, the network's predicted sequence of images is comparable with the ground truth sequence of images. The training loss for the entire data is 0.00038 for 260k iteration, and the testing loss is 0.00052. Training and testing execution is done on NVIDIA GeForce RTX 3090 dual GPU machine. The time taken to train the DPAI model is about 32 hours.

We have used a trained network as a predictive model for emulating time-domain ultrasonic wave propagation. We have adopted a continuous prediction strategy for predicting the successive 5-frames in a sequence by continuously providing the previous 10-frames as input to the DPAI model. We have provided an initial input mini-batch of frames from FE analysis; then, the predicted frames are given as input to form a closed loop for predicting the entire simulation. This procedure continually loops until all frames are anticipated until total frames are generated in a simulation. In this procedure, frames from the FE simulation are supplied for the first iteration, and the result from the previous iteration is used as input to forecast the next set of frames for the succeeding iterations.

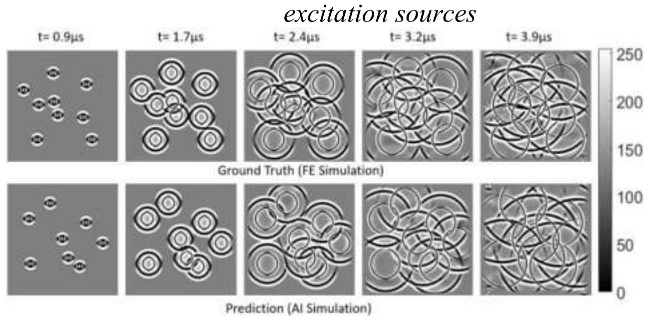
We have modeled three different FE simulations with three excitation, six excitation, and nine excitation point sources to predict the forward wave propagation simulation. To determine the trained network's efficiency, we need to examine qualitatively by comparing the DPAI-modeled simulation with the FE simulation and comparing the A-scan extracted from the AI-predicted simulation and FE simulation at model center pixel locations within the frame. Training and testing execution is done using the same computer hardware. The predictive network takes approximately 2 minutes to generate 675 frames of a single simulation. With this approach, we could successfully reduce the computational overhead to a greater extent, which is 20X faster than the conventional FE solver.



(a) *Comparison between AI/FE simulation for the single excitation source.*

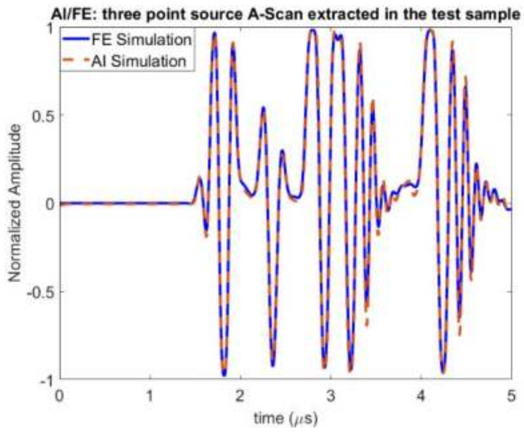


(b) *Comparison between AI/FE simulation for four excitation sources*

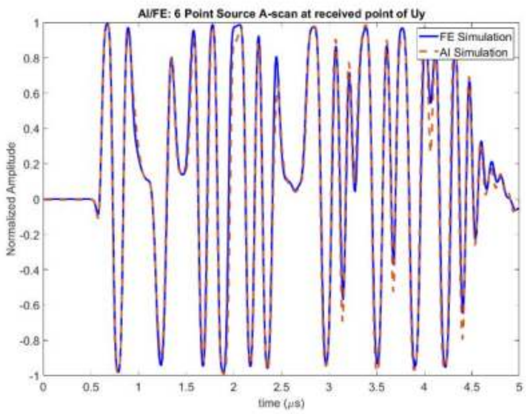


(c) *Comparison between AI/FE simulation for five excitation sources*

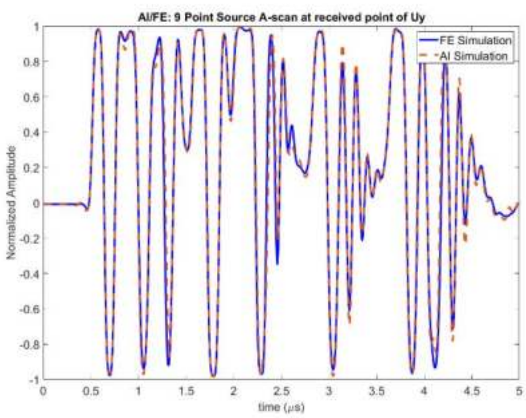
Figure 3*: A qualitative comparison between FE simulation with DPAI-generated simulations for the deeper time period of* ***(a)*** *three,* ***(b)*** *six, and* ***(c)*** *nine excitation sources for spatial features information and time evolution of ultrasonic wave dynamics.*



(a) *Three excitation point sources: A-Scan*



(b) *Six excitation point sources: A-Scan*



(c) *Nine excitation point sources: A-Scan*

Figure 4*: Extracted FE simulation-based A-Scan is compared with DPAI predicted simulation-based A-Scan to validate the effectiveness of the DPAI predictive model for wave propagation simulations at the centre of the frame's location for three* ***(a)****, six* ***(b),*** *and nine* ***(c)*** *excitation sources.*

Figure 3(a)-(c) shows the wave propagation phenomenon evaluation over time for three, six, and nine excitation sources. *Figure 3(a)* describes the three excitation sources for spatial feature evaluation of FE and DPAI simulations over time. *Figure 3(b)* shows the ultrasonic wave propagation evaluation for six excitation sources for the top row FE and the bottom AI predicted simulation. Finally, *Figure 3(c)* evaluated spatial-temporal wave dynamics in the solid medium for nine excitation sources on top-ground truth and bottom DPAI. As seen in *Figure 3*, the predicted frames are identical to the ground truth; these are qualitatively in good agreement in terms of constructive-destructive interference at wave interaction and spatial feature evaluation. We have extracted an A-Scan at a center location inside DPAI-predicted and FE simulation frames to validate each predicted frame, acting as the transducer position shown in

Figure 4(a)-(c) for three, six, and nine excitation sources, respectively. The A-Scan is used to identify the error between the predicted and ground truth for each frame at the transducer location. We have observed that its magnitude falls within 2% error for all the scenarios A-scan according to mean square error over the entire simulation; it will be true as long as the field values are not entirely zero.

4.2 Simulating Reflection Wave Propagation from Irregular Boundaries Using the DPAI Model:

The second DPAI model is trained using the dataset obtained for reflection borders to model the propagation of reflection waves at irregular edges. A similar training methodology is employed to train the DPAI, described in section 4.1. With the exception of the number of epochs and the kernel size being altered to 3 x 3, the DPAI model architecture and layer count are comparable to section 4.1. There are 256 hidden dimensions in every encoder or decoder structure. Over 400 epochs, the average loss value is 0.00042, and the testing loss value is about 0.00068. *Figure 5(b)* shows that the loss value stabilizes as the number of epochs grows. 45 hours are needed to train the DPAI model using an NVIDIA GeForce RTX 3090 dual GPU machine.

In order to expand the scope of the DPAI model, we have examined the propagation of ultrasonic waves in two distinct irregular geometrical domains. A comparison is made between the FE and the anticipated simulation of the DPAI model. *Figure 6* shows the reflected ultrasonic wave propagation for irregular geometrical shapes. *Figure 6* has simulations from the FE in the top row and the

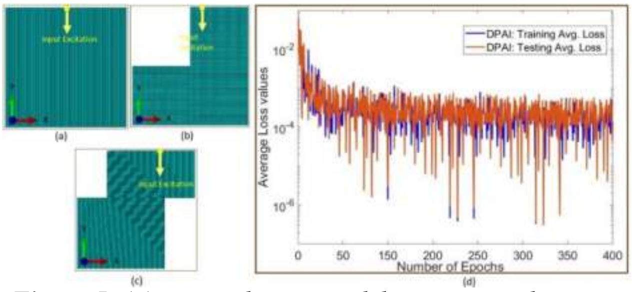
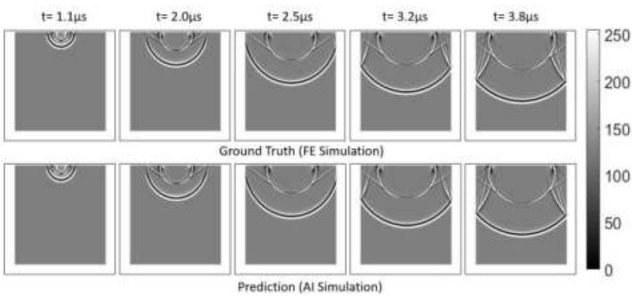
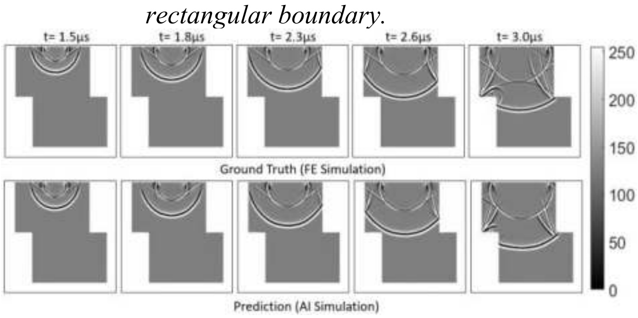


***Figure 5**: (**a**) Finite element models: To create the training dataset, FE models with single point sources are excited in the Y direction at the top surface of the domains. (**b**) DPAI: Training/Testing: The model was trained using the reflection from the boundary datasets, the model average training, and the testing loss throughout the number of epochs.*



***(a)** FE/DPAI simulation comparison for the rectangular boundary.*



***(b)** FE/DPAI simulation comparison for the irregular geometry*

***Figure 6**: Reflected wave propagation with irregular geometrical boundaries: The DPAI model is implemented to simulate the wave propagation simulation in the various irregular geometrical domains. The sequence of frames generated using FE and DPAI simulations are compared at multiple time instants. The 5 MHz central frequency with two cycles is used to model the simulation from DPAI and FE for the rectangular domain (**a**) and irregular geometry shape in (**b**), respectively.*

anticipated simulation from the DPAI model in the bottom row. The suggested DPAI model is trained with boundaries that have straight edges, but it can produce simulations with irregular. The DPAI model is capable of producing reflection wave propagation from sharp edges as it has learned wave interaction physics at the domain edges from the training datasets. Thus, the DPAI model matches the FE and correctly predicts the propagation of reflection waves from the side and back walls.

4.3 Simulating Phased Array Beam Steering Wave Propagation Simulations using DPAI:

The third DPAI model is trained using the dataset generated by modelling the phased array beam steering simulations in FE simulations. We employ the same DPAI architecture as section 4.1. Using NVIDIA GeForce RTX 3090 GPU processors, the DPAI model is trained for minimizing the mean square loss function by back-propagation through time (BPTT) at a linear rate of 0.0001 over 300 epochs. The training procedure takes around 56 hours. As seen in *Figure 7(b),* the testing loss is calculated to be 0.00025, and the average training loss is 0.00078. The FE simulation dataset is used to evaluate the trained DPAI model in order to quantify its efficiency.

We have taken into consideration a variety of phased array beam steering simulations aside from the ones utilized during training and testing in order to evaluate the trained DPAI model qualitatively. The DPAI model receives the preceding 10 frames as input and outputs the next 5 frames to create the full simulations. This procedure loops up to the entire number of sequences of frames produced in a series. The initial frames obtained from the FE simulation are given as input for the first iteration of the simulation-generating process. The output of the previous iteration's generated frames is used as input in the subsequent iteration to complete the full-length simulations.

With the phased array beam steering angle set to 30 degrees, *Figure 8* depicts the wave propagation sequence of frames at the same time occurrences between DPAI and FE. In particular, we present the FE and DPAI simulation at exact time instances t = [0.9 μs, 1.1 μs, 1.5 μs, 1.9 μs, 2.2 μs] for the long-term simulation. The top row in *Figure 8* shows the FE (ground truth) sequence, while the bottom row reports the DPAI simulation. It is evident that there is a robust qualitative agreement between the DPAI-generated simulations and the FE simulations.

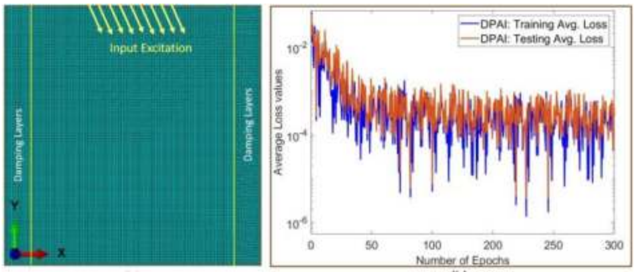


***Figure 7**: **(a)** FE modeling: all the active aperture elements are triggered in parallel using pre-defined delay laws to form the ultrasound beamforming to steer in the medium. **(b)** DPAI: Training/Testing: the average loss values over a number of epochs for phased array beam steering datasets.*

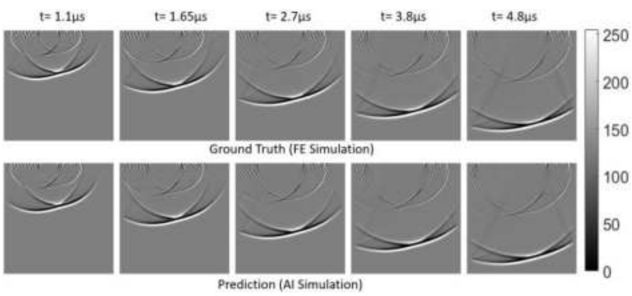


***Figure 8:** Phased array beam steering simulation*

The DPAI model performance in simulating the phased array beam steering simulation is compared with FE. In FE, a 16-element active aperture is used for generating simulation with the central frequency of 5 MHz with two cycles. The 30-degree beam steering pre-calculated focal law is applied in FE. The FE generated in the first 10-frames is fed to DPAI for generating successive next 5-frames.

The phased array (PA) ultrasonic technology allows for beam steering and focusing without requiring the transducer to move physically, it is the most advanced method for defect characterization and identification in the NDE domain. The main benefit of the PA technique over the traditional ultrasonic technique is that it is much faster to inspect large regions from a single location using a variety of ultrasonic profiles, such as beam and plane wave steering and focusing, without having to move the transducer.

5 Conclusion:

This work presents a novel and innovative deep learning DPAI approach for rapid computation of the ultrasonic wave propagation for point sources, reflection from boundaries, and phased array beam steering simulations. The method is trained using spatial-temporal FE simulation data. The DPAI model is learning representations of time-domain elastodynamic simulations from training datasets. In order to simulate the propagation of ultrasonic waves, data-driven, physics-aware AI prediction algorithms are used. A DPAI model is significantly faster than a conventional FE solver in computing simulation. The trained DPAI model enables users to simulate significantly larger domain simulations, single to multiple excitations point sources, reflection from irregular geometrical boundaries, and phased array beam steering ultrasonic wave propagation in 2D. The data it yielded demonstrated the suggested DPAI's efficacy in accurately replicating wave propagation phenomena. In this article, we first trained the AI network only by simulation of the wave transmission phenomena, and we were able to obtain the expected outcomes for the wave dynamics assessment for forward and reflection from boundaries. In further research, we will place many defect classes and their combinations to mimic different wave propagation scenarios, such as reflection, refraction, creeping, and scattering effects.

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AI-Driven CFRP Structure Evaluation: Deep Learning-Powered Automated Air-Coupled Ultrasonic Detection of Defect

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Abstract

In this study, the successful experiments with air-coupled ultrasonic testing (ACUT) conducted on a 300 mm x 300 mm CFRP laminate, constructed from unidirectional Carbon Fibres, has been designed to simulate various types of damage during manufacturing, were presented as part of the experimental data. It was noted that the ACUT results exhibited strong correlations with the ground truth. To improve automated defect detection, a two-stage process was introduced. In the initial stage, C-Scan data acquired from the ACUT system was utilized. This data underwent meticulous analysis by a Convolutional Neural Network (CNN) image classifier, which categorized the images into two primary classes: defects and non-defects. Subsequently, defect instances underwent in-depth processing using Mask R-CNN, a technique that generated bounding boxes and segmentation masks for each defect zone within the images. The entire process was executed utilizing TensorFlow. The ultimate objective of this approach was to provide inspectors with the requisite tools to promptly and accurately discern and assess defects in composite materials, with the potential to substantially enhance the efficiency and precision of quality control processes in composite structures.

Keywords: *Ultrasonic-Testing, Defect identification, Carbon Fiber Reinforced Polymers, Convolutional neural networks*

1 Introduction

Composites, both in a broader context and with a specific focus on Carbon Fibre Reinforced Polymers (CFRP), have become critical needs across a range of applications, notably in aerospace and automotive industries. This popularity is attributable to their outstanding mechanical attributes, including their lightweight nature, high specific strength, and suitability for tailored designs [1-3]. Ultrasonic Testing (UT), Radiographic Testing (RT), Thermographic Testing, Shearography, and Acoustic Emission (AE) Testing are well-established non-destructive inspection methods for composite structures. UT employs high-frequency sound waves for defect detection and characterization [3-4], RT uses X-rays or gamma rays to reveal internal anomalies [5-6], Thermographic Testing relies on thermal imaging to identify defects [7-8], Shearography measures surface deformation under stress [9-10], and AE Testing monitors acoustic signals during material deformation or failure [11-12]. The choice of method depends on factors such as material properties, defect types, sensitivity requirements, and resource availability. Often, a combination of these techniques is employed to ensure a comprehensive assessment of composite structural integrity. It is important to note that these aforementioned NDT methods represent only a subset of the conventional techniques employed for the assessment of composite structures. The selection of an appropriate method depends on several factors, including the composite material type, the nature of expected defects, required sensitivity, and the availability of necessary resources and equipment. Often, a combination of these methods is employed to ensure a comprehensive evaluation of the structural integrity of the composite structure. The ongoing transition to Industry 4.0 presents new opportunities for advancing inspection procedures through artificial intelligence (AI)-based machine learning and deep learning algorithms, enabling sophisticated data analysis and autonomous systems. Several research groups have used deep learning (DL) algorithms to detect defects in different structures and materials, including A-scan ultrasonic signals, B-scan images, and phased-array ultrasonic images. It is noteworthy that, DL models outperform the traditional methods and even human operators in some cases. Different DL architectures such as Convolutional neural networks (CNNs), Gated recurrent unit (GRU), Scalable and Efficient Object Detection (EfficientDet), and Visual Geometry Group(VGG-16) [21], have been applied to process ultrasonic data, and transfer learning has proven effective in enhancing model performance. These studies collectively suggest that the automation of repetitive NDE tasks is achievable in the medium term, with DL methodologies providing higher accuracy and efficiency than classical approaches.

Guo *et al.* [13] introduced a DL model that combines GRU and CNN architectures to process ultrasonic signals, achieving superior accuracy compared to other networks. Yan *et al.* [14] applied a CNN-Support Vector Machine(SVM) framework for pipeline girth cracking identification using Electro Magnetic Acoustic Transducer (EMAT) signals, outperforming traditional feature extraction methods. DL has also been employed in the context of ultrasonic B-scans for defect detection. Yuan *et al.* [15] utilized a Feed-forward neural networks (FCNN) framework for train wheel defect identification, achieving a 92% recognition rate. Medak *et al.* [16] proposed an EfficientDet network for automated defect detection from ultrasonic B-scan images, outperforming other DL models. Virkkunen *et al.* [17] compared a CNN model's performance to human operators for phased-array ultrasonic B-scan flaw detection, demonstrating the CNN's superiority. Slonski *et al.* [18] explored the automation of flaw detection in concrete through ultrasonic tomography images using a VGG-16 network, reporting a validation accuracy of 97%. Additionally, Ye *et al.* [19] compiled a comprehensive dataset of ultrasonic wavefield images and benchmarked various well-known DL models, revealing DenseNet as the most accurate. These examples collectively demonstrate that DL methodologies have surpassed classical methods and human operators in NDE tasks, offering potential for automating repetitive inspections in the near future.

A. Croxford *et al.* [20], introduces a framework of automation levels for various non-destructive evaluation (NDE) modalities, with a primary emphasis on ultrasound inspection. The proposed levels, depicted in Fig.1, span from traditional NDE procedures where human operators are fully responsible to a future scenario of complete NDE automation without human intervention. Levels 3 and 4 represent fully automated NDE, feeding directly into structural integrity decision-making, enabling data-driven approaches for decisions like acceptance, rejection, maintenance, repair, and remaining useful life estimation. These proposed levels align with the levels recently published by the European Union Aviation Safety Agency (EASA) and are extended here to address a broader range of ultrasonic NDE applications. The transition to higher automation levels is greatly facilitated by the adoption of Deep Learning (DL) methods, enabling more sophisticated automation in handling complex scenarios with minimal operator involvement and the potential for human-free decision-making. However, the need for substantial labelled datasets presents a challenge, which can be mitigated by employing rudimentary DL systems to coarsely label data.

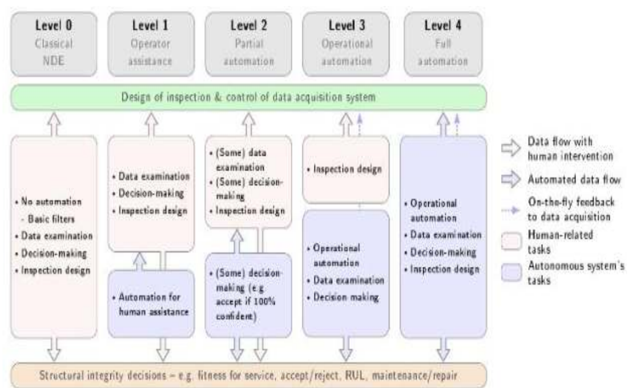


***Fig.1**: Schematic representation of the proposed level of automation by A. Croxford et al.[20]*

At CSIR-NAL, the pursuit of automated ultrasonic inspection is a primary objective. To initiate this automation, as suggested by A. Croxford *et al.*, the air-coupled ultrasonic testing (ACUT) experiments were conducted on a 300 mm x 300 mm CFRP laminate to generate database. In order to improve the process of automated defect detection, a two-stage strategy was implemented. In the first stage, a Convolutional Neural

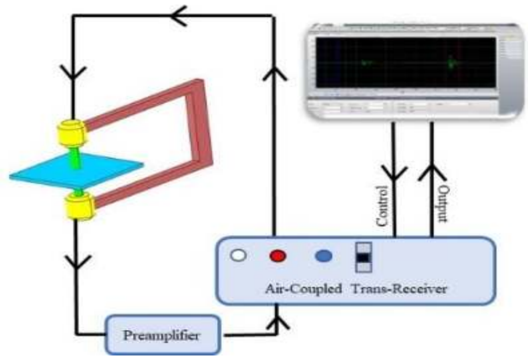
Network (CNN) image classifier use to categorize images into two primary classes: defects and non-defects. Subsequently, further refinement was achieved by subjecting defect instances to comprehensive processing using Mask R-CNN, a technique for generating bounding boxes and segmentation masks delineating each defect zone within the images. The entire workflow was carried out with the aid of TensorFlow-2.20 and NVIDIA CUDA Cores:10752. The overarching aim of this methodology was to furnish inspectors with the requisite tools for the rapid and precise identification and evaluation of defects present in composite structure.

The organization of the paper is as follows: sec.2 describes the experimental setup and specimen under test; sec.3 describes model development. In sec.4, discuss results, by conclusion in sec.5.

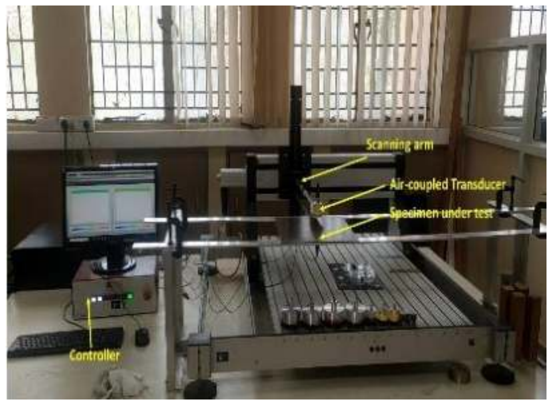
2 Experimental Setup & Specimen Under Test

Air-coupled ultrasonic testing has demonstrated its high reliability as a technique for inspecting defects in contemporary multilayer composites, encompassing assessments of delamination, air inclusions, bonding quality, and impact-induced damage.

The Air-coupled system developed by The Ultran Group represents a precise system for damage detection in a wide range of materials across various industries illustrated in Fig.2. It includes a fully configured ultrasonic analysis system suitable for both internal and surface imaging, enabling the investigation of defects, heterogeneity, delamination, porosity, velocity/density, thickness, and Time of Flight. The system supports ULTRAN's proprietary scanning package for 2D C-Scan imaging, SecondWave^{TM} Studio software for A-scan point measurements, Line-Scan, and FFT analysis, as well as SecondWave^{TM} Research Studio software for post-processing and statistical evaluation of C-Scan images.



(a)

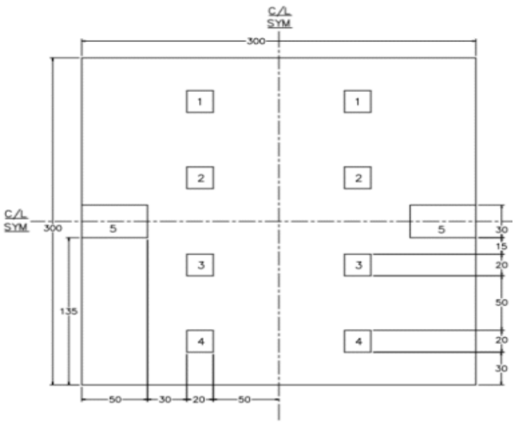


(b)

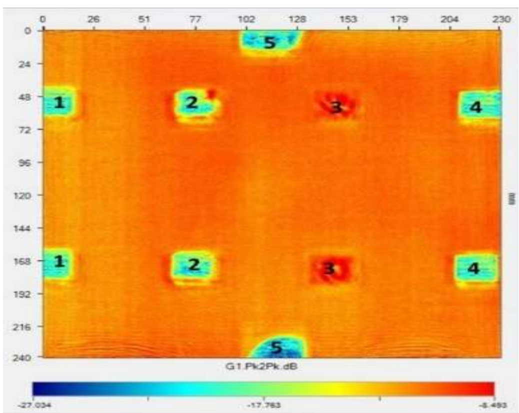
Fig.2: *(a) Air-Coupled ultrasonic system, comprising a controller, a scanning area, and holders for transducers (b) Picture depicting the system at CSIR-NAL*

A 300mm x 300mm laminate, fabricated from unidirectional Carbon Fibres, has been designed to simulate various types of damages that can occur in composite laminates during manufacturing, as illustrated in Fig.3a. The figure indicates specific insert damages: "1" represents a release film with a 20x20 mm insert, "2" signifies a 20x20 mm UD prepreg backup film insert, "3" denotes a 20x20 mm UD prepreg backup paper insert, "4" corresponds to a 20x20 mm tool tech insert, and "5" indicates a 50x30 mm delamination area within the laminate. The ACUT system combines two point-focused piezoelectric transducers, each with a 38 mm focal length and a valid inspection region with a 13 mm radius. This transducer arrangement facilitates the transmission of bulk waves within CFRP specimens. The ultrasonic signals, generated at a frequency of 140 kHz, are transmitted with a controlled transitional velocity of 10 mm/s in both the horizontal (V_x) and vertical (V_y) directions. The scanning process utilizes a step size of

0.1 mm, ensuring precise coverage of the specimen. Moreover, the system features a gain setting of 70 dB, resulting in enhanced signal sensitivity and detection capabilities. Raw C-Scan image obtained from the system is illustrated in Fig.3b.



(a)



(b)

Fig. 3: *(a) Laminate Design and Damage Simulation: A 300 mm x 300 mm unidirectional CFRP laminate designed to simulate various manufacturing-induced damages within composite laminates (b) Unprocessed C-Scan image rotated 90° Anti-Clockwise relative to Fig. 3a*

2.1 Data Set Generation

In accordance with the procedures detailed in the experimental setup section, we conducted data acquisition by systematically varying parameters including pulse repetition frequency (PRF), transmitter voltage (V), Low-Pass Filter (LPF) and High-Pass Filter (HPF) settings, and adjusting the receiver gain of the ACUT system. This process yielded a total of 63 images. Subsequently, we employed data augmentationtechniques, such as image rotation at various angles, flipping, scaling, cropping, brightness enhancement, contrast adjustment, and the adding white noise to the images. These augmentation methods allowed us to expand our dataset to a total of 321 images for further analysis and experimentation.

3 Model Development

As outlined in sec. 1, our objective was to develop an algorithm for shape detection and damage size estimation within the test specimen. To achieve this, we adopted a two-stage approach, as illustrated in Fig.4. In the first stage, as indicated in the flowchart, we performed CNN based classification on the C-scan image of the test panel. Subsequently, at stage-2, in cases where damage was detected, we utilized Mask-RCNN on the C-scan images to identify arbitrary shapes and calculate the extent of the damage.

The raw C-scan image, initially sized at [1000, 600], was subjected to de-noising (optional) and evaluated by a CNN-based classifier to ascertain the presence or absence of damage in the input image. We opted for a CNN-based Classifier due to its proven ability to accurately recognize damage in images, its capacity to autonomously learn and extract intricate features, and map them to their respective classes, ensuring precise image classification. Furthermore, CNNs exhibit adaptability to diverse damage sizes, scales, and orientations.

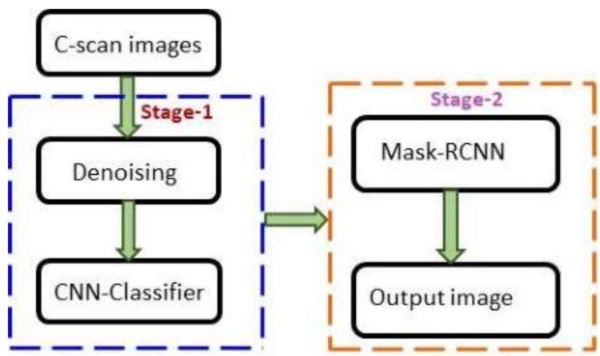


Fig.4: *Flowchart representation of the Model: Classifying C-scan images in the first stage and, when damage is detected, using Mask R-CNN to identify shapes and measure the damage's extent in the second stage*

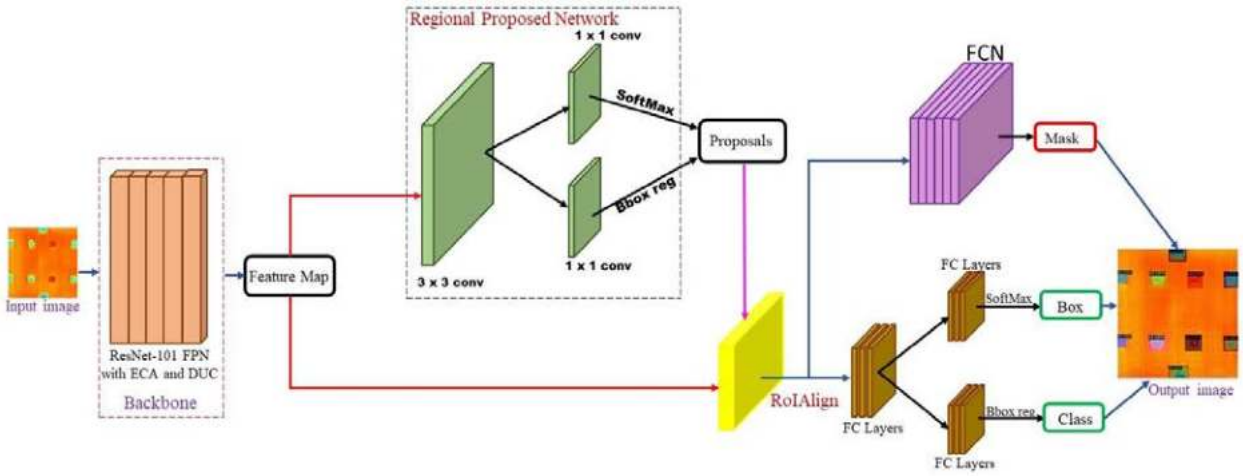


***Fig. 5:** Mask R-CNN architecture for defect zone bounding boxes and segmentation masks*

After damage has been classified, the input image is first passed through a backbone network, which is typically a deep convolutional neural network (CNN) like ResNet-101 and Feature Pyramid Network (FPN) architecture. The backbone network extracts a set of feature maps at different scales, representing features from low-level edges and textures to high-level object and context information as illustrated in Fig.5.

By applying ResNet-101 to our data set, the method gives Pool size as 7, Maximum pool size as 16, Mask shape [28, 28], ROI positive ratio 0.33. The weights of each feature have been calculated based on minimum values, maximum values, and standard deviation of the objects.

In the image processing pipeline, the first step involves calculating the number of pixels and their intensity in the input image, using a utility function that extracts information from a NumPy array to obtain details about bounding boxes, including shapes, minimum, and maximum values. The kernel function used for processing is a [3x3] filter, and the image is compressed to a 0-255 scale.

For segmentation, the input image is passed through a Region Proposal Network (RPN), it plays a critical role in identifying potential defect recognition, improving the overall efficiency and accuracy of the Mask R-CNN model in image segmentation tasks. It achieves this by sliding set of anchor boxes of different scales and aspect ratios across the feature map produced by a backbone Network. The RPN then predicts the likelihood of each anchor box containing an object and refines their positions with multiple bounding boxes regression.

After defining the regions, the output of the RPN and feature maps from RES-NET101 and Feature Pyramid Network (FPN) will be the input of the is RoI Alignment or RoI Pooling techniques which is a Pooling layer, where the size of the proposed regions can be determined.

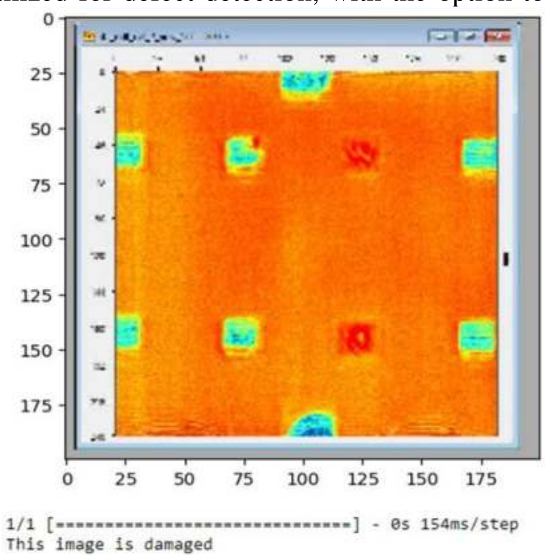
Features obtained from RoI alignment are set for the model and passed through Fully Connected Layers (FCL) and Fully Connected Network (FCN). This step aids in visualizing how to design and generate masks over an image.

The model is pre-trained on the COCO dataset [21], which consists of over 330,000 images, each annotated with 80 object categories and 5 captions describing the scene. Weights for each feature are calculated based on minimum values, maximum values, and the standard deviation of objects.

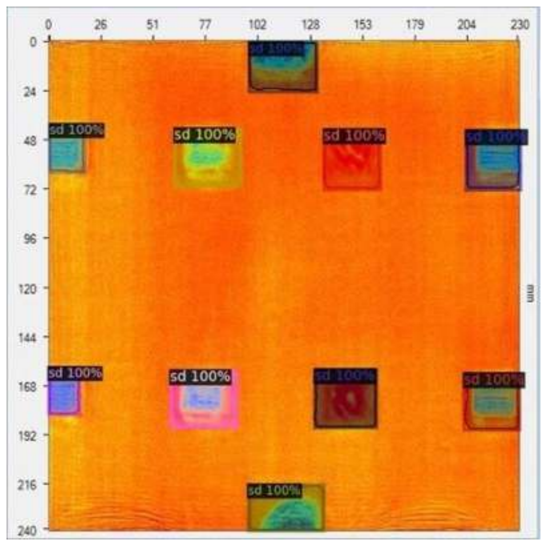
We have presented one of the sample C-Scan image of our data set from stage -1 to stage-2 in Sec.4

4 Results

In this study, we present two key outcomes. First, we describe the outcome of the classification process conducted using a CNN-Classifier implemented through Keras illustrated in Fig.6a. Subsequently, performance of the Mask R-CNN algorithm illustrated in Fig. 6b, which was initially trained to detect various defects and shapes based on specific detection requirements. The model demonstrated satisfactory performance across most detection tasks. Pre-trained weights are available for the Mask R-CNN model and can be utilized for defect detection, with the option to update these weights during subsequent model training. To refine the model's ability to identify objects and shapes, we conducted further training using our dataset that included various shapes. The model underwent training and validation testing, achieving a mean Average Precision (mAP) of 89% after 1000 epochs. The validation loss function plateaued at 0.004, while accuracy consistently remained around 0.988 for our dataset. These findings demonstrate the model's capacity to effectively detect both small, clustered objects within a single image and larger or medium-sized objects in an image.



(a)



(b)

***Fig.6:** (a) CNN Image classifier: Whether the image is damage or not (b) Mask R-CNN: Creates a mask over the damage area*

5 Conclusion

Ultrasonic testing (UT) is one of the most widely used non-destructive inspection methods for inspection of composite structure. The artificial intelligence (AI) based machine learning and deep learning algorithm play a critical role in facilitating the advancement of automated inspection procedures for UT data. In this context, air-coupled ultrasonic testing (ACUT), we have successfully conducted experimental using composites panels with and without defect. ACUT results shows good correlation with ground. To facilitate automated defect detection, our algorithm employs a two-stage process. In the initial stage, we utilize C-Scan data generated by the ACUT system and analysed through a Convolutional Neural Network (CNN) image classifier, responsible for classifying the images into two categories: defects and non-defects. Subsequently, the defect instances are processed using Mask R-CNN, which generates bounding boxes and segmentation masks for each defect zone within the image with mPA of 89%. This process is implemented using TensorFlow. The the model's accuracy can increase further, by adjusting the hyperparameters, which can encompass aspects like kernel types, regularization strengths, or learning rates.

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NDE PATENTS

Dr. Shyamsunder Mandayam

Through this feature every quarter, we intend to provide you a snapshot of some latest and important patents in the world of NDE. We also intend to use this feature to encourage the Indian NDE community to file more patents based on your innovations. We will be happy to provide guidance and assistance in different ways – Answering queries, Conducting Tutorials and webinars, One-on-one discussions, Networking with Intellectual property experts, etc.

Need help understanding? What are Patents? Why to Patent? When to Patent? What is the Patenting Process? …… Please feel free to reach out to me by email at mandayam.shyamsunder@gmail.com

Here we list below a few interesting Indian patents related to a mix of different modalities in ***NDE and Inspection.***

Indian Patent 201941027800

Method for Simulation Assisted Data Generation and Deep Learning Intelligence creation in Non-destructive Evaluation Systems

Inventors: Krishnan Balasubramanian

Assignee: Indian Institute of Technology, Madras (IIT Madras), INDIA

Method and system for detecting one or more anomalies in an object are provided. The system receives experimental data of the object and applies a probability density function (PDF) upon one or more variables associated with the experimental data to determine corresponding one or more PDF estimates. The system further generates simulated data associated with the object based on at least one of the one or more PDF estimates and priori data associated with the testing of the object. The simulated data comprises one or more new anomalies unknown in the experimental data along with the one or more anomalies of the experimental data. Furthermore, the system trains a learning model based on the one or more new anomalies and the one or more anomalies of the experimental data. The learning model is applied for detecting any anomaly in an object.

Indian Patent 201931003327

A Method of Non-destructive Evaluation of Turbo Generator end Retaining rings using Eddy Current

Inventors: Antony Harison M.C and M Swamy

Assignee: Bharat Heavy Electricals Limited, Hyderabad, INDIA

The array eddy current testing method includes placing a probe-encoder assembly on the surface of the retaining ring such that there is good contact between the coil elements and the surface. The probe is them moved along the surface for gathering eddy current signal. Signal from each of the coil elements are collected and processed to from a true surface image. A surface image formed using eddy current signal response gives a top view of the surface with the defect locations, if any. Position encoder which is attached to the probe casing precisely records the distance covered by the probe during scanning while acting as a trigger for data collection. Using this technique, the non-destructive evaluation of the end retaining rings becomes more reliable and faster. Also, it is easy to interpret the signals from the surface image generated. After the presence of a surface/sub surface defect is detected, it is easy to pin point the location of the defect on the ERR surface with the encoder data.

Indian Patent 201641024212

Guided-wave mode selected Ultrasonic transducers for Leave-in-Place High-temperature bulk- Non-destructive Evaluation, based on Magneto strictive Amorphous Metallic Strips

Inventors: Antony Jacob Ashish, Prabhu Rajagopal and Krishnan Balasubramaniam

Assignees: Indian Institute of Technology – Madras, INDIA

The invention relates to a guided wave mode selected ultrasonic transducers for leave-in-place high-temperature bulk-non-destructive evaluation, based on magneto strictive amorphous metallic strips. The high Curie temperature of amorphous metallic strip used as magneto strictive core enables transducer to operate at extended durations in elevated temperatures up to 300ºC. The arrangement is on the basis that the guided wave mode whose mode structure possess a certain pattern in which the distribution of stress is more concentrated around the geometric centre of the waveguide, would yield maximum transmission of ultrasonic waves into the bulk structure.

Indian Patent 011680857B2

ELECTROMAGNETIC NONDESTRUCTIVE MATERIAL CHARACTERIZATION OF DIELECTRICS DEPLOYING PLANAR EBG BASED TRANSMISSION LINE SENSOR

Inventors: Malathi Kanagasabai, Vimal R. Samsingh, S. Sangeetha, P. Yogeshwari, Safrine Kingsly

Assignee: Anna University, INDIA.

The present invention is a novel non-invasive electromagnetic method of characterization of the electrical properties of dielectrics. Planar microstrip transmission line method has been employed to measure the complex permittivity of the dielectric materials. The transmission line carrying microwave signals is bridged on both sides by Electromagnetic Band gap structures which notches only 2.4 GHz. The dielectric is loaded on this transmission line. The notched frequency information and the magnitude of the transmission response is observed for various materials whose real part of permittivity and loss tangent values are known. The proposed model exhibits an R-square measure of goodness of fit of 99.83% for the real part of permittivity and 96.67% for the imaginary part of permittivity.

Indian Patent 7149/CHENP/2015

Systems and Methods for Non-destructive Evaluation of Molds and Crucibles used in Investment Casting

Assignee: General Electric Company

The present disclosure relates to systems and methods useful for non-destructive evaluation (NDE) of moulds and crucibles used in investment casting processes including without limitation for producing aircraft engines land-based turbine engines and the like. According to one aspect the present disclosure provides a system for non-destructive evaluation that includes a support a 3D scanning device and a computer component. According to another aspect the present disclosure provides a method for non-destructive evaluation that includes the steps of: providing a system for non-destructive evaluation of a mould or crucible according to the present disclosure; securing a mould or crucible to the support of the system; and operating the 3D scanning device of the system in conjunction with the computer component in order to create a 3D structure difference map that indicates whether the mould or crucible falls within or outside a desired structural integrity parameter range.

Indian Society for Non-destructive Testing (ISNT)
Enriching Lives through NDE

CIRCULAR

No: ISNT/2023/01 **Date: 2nd January 2023**

Schedule of ISNT meetings
YEAR: 2023

Month	Meeting	Day/Date of mtg.	Timing	Mode / Venue
JANUARY 2023	Past President's Meeting	**Sunday, 8th January**	03:30 pm–05:30 pm	**ONLINE**
	Finance / Treasurers Meeting	**Saturday, 21st January**	03:30 pm–05:30 pm	**ONLINE**
FEBRUARY 2023	Byelaw Enforcement & Advisory and RA Committee	**Saturday, 4th February**	03:30 pm–05:30 pm	**ONLINE**
MARCH 2023	Chapter Chairmen Meeting	**Saturday, 4th March**	03:30 pm–05:30 pm	**ONLINE**
	PFMB	**Saturday, 11th March**	10.00 am– 11.30 am	**HYBRID** Online / ISNT HO, Chennai
	TMB		11.45 am – 1.30 pm	
	NCB		2.30 pm – 4.30 pm	
	NGC	**Sunday, 12th March**	10.00 am – 3.30 pm	
MAY 2023	Finance / Treasurers Meeting	**Saturday, 20th May**	03:30 pm–05:30 pm	**ONLINE**
JUNE 2023	PFMB	**Saturday, 10th June**	10.00 am– 11.30 am	**HYBRID** Online / ISNT HO, Chennai
	TMB		11.45 am – 1.30 pm	
	NCB		2.30 pm – 4.30 pm	
	NGC	**Sunday, 11th June**	10.00 am – 3.30 pm	
JULY 2023	Past President's Meeting	**Sunday, 9th July**	03:30 pm–05:30 pm	**ONLINE**
AUGUST 2023	Byelaw Enforcement & Advisory and RA Committee	**Saturday, 5th August**	03:30 pm–05:30 pm	**ONLINE**
SEPTEMBER 2023	Chapter Chairmen Meeting	**Saturday, 2nd September**	03:30 pm–05:30 pm	**ONLINE**
	PFMB	**Saturday, 9th September**	10.00 am– 11.30 am	**HYBRID** Venue to be decided by March NGC
	TMB		11.45 am – 1.30 pm	
	NCB		2.30 pm – 4.30 pm	
	NGC	**Sunday, 10th September**	10.00 am – 3.30 pm	
	Finance / Treasurers Meeting	**Saturday, 16th September**	03:30 pm–05:30 pm	**ONLINE**
OCTOBER 2023	Award Committee	**Saturday, 14th October**	03:30 pm–05:30 pm	**ONLINE**
DECEMBER 2023	PFMB	**Wednesday, 6th December NDE 2023**	02.00 pm– 03.00 pm	**PHYSICAL** NDE 2023 Venue, Pune
	TMB		03.00 pm - 04.00 pm	
	NCB		04.30 pm– 0530 pm	
	NGC		05.30 m - 07.30 pm	

Notes: 1. Separate notifications will be sent to the members of the committee / Board for each meeting
2. Each meeting should be attended only by the members and invitees

Bikash Ghose
Hon Gen Secretary, ISNT

The First International Conference on NDE 4.0 - April 2021 in Virtual Mode

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