Advanced Non-Destructive Testing Techniques For Pipeline Integrity Assessment

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Abstract. The paper reviews advanced non-destructive testing techniques of pipeline integrity assessment mainly applied for defect detection, such as corrosion, cracks, and mechanical damage, with no disturbance to the pipeline operational services. Accordingly, the essential NDT methods reviewed will be classified as ultrasonic testing, electromagnetic inspection, radiographic testing, acoustic emission testing, and intelligent pigging. Each technique's detection accuracy, cost-effectiveness, and field applicability have been reviewed and judged. Among various comparisons done here, one points out strengths and weaknesses. At the same time, it indicates the rise of artificial intelligence for predictive maintenance, coupled with a completely different generation of IoT sensors that allow real-time monitoring. However, knowledge gaps still exist regarding standardisation, real-world validation of new technologies, and cost-efficient solutions for the complex geometries of pipelines. Finally, it concludes with recommendations for improving pipeline safety, operational reliability, and efficiency in maturing energy infrastructures.

Keywords: Non-Destructive Testing; Pipeline Integrity; Predictive Maintenance; Evaluation Techniques; Real-Time Monitoring

INTRODUCTION

Pipelines are critical components of global energy infrastructure, transporting oil, gas, and other essential resources across vast distances. Ensuring the structural integrity of these pipelines is vital to avoid catastrophic failures that could lead to economic loss, environmental damage, and safety hazards. Over time, pipelines are subject to deterioration due to corrosion, mechanical stress, and material fatigue, which can compromise their integrity [1]. As a result, the need for

advanced monitoring techniques has become more urgent, pushing the development and adoption of non-destructive testing (NDT) methods. Traditional pipeline inspection methods, such as visual and hydrostatic testing, are often invasive, time-consuming, and limited in detecting hidden or subsurface flaws [2].

Furthermore, pipelines are often located in remote or harsh environments, making access and regular monitoring difficult. These challenges have underscored the need for advanced techniques to detect potential issues early and ensure

continuous monitoring of pipelines without causing damage. Non-destructive testing (NDT) has gained significant traction in pipeline integrity management because it offers the ability to assess the condition of pipelines without interrupting operations. NDT methods rely on various physical principles – such as ultrasonic waves, electromagnetic fields, and radiographic imaging – to detect internal defects, cracks, or corrosion [3]. These techniques enable operators to monitor pipelines in real-time, providing critical data to prevent failures. The continuous evolution of NDT technologies and the integration of artificial intelligence (AI) and real-time monitoring systems have allowed for a more proactive approach to pipeline maintenance [4]. The primary aim of this review is to provide an in-depth analysis of the latest advancements in non-destructive testing techniques for pipeline integrity assessment. The review will evaluate the strengths, limitations, and applications of various NDT methods, focusing on their effectiveness in detecting pipeline defects and their potential for real-time monitoring. This review also seeks to highlight existing gaps in research and technology, offering insights into areas that require further development to enhance the safety and reliability of global pipeline networks.
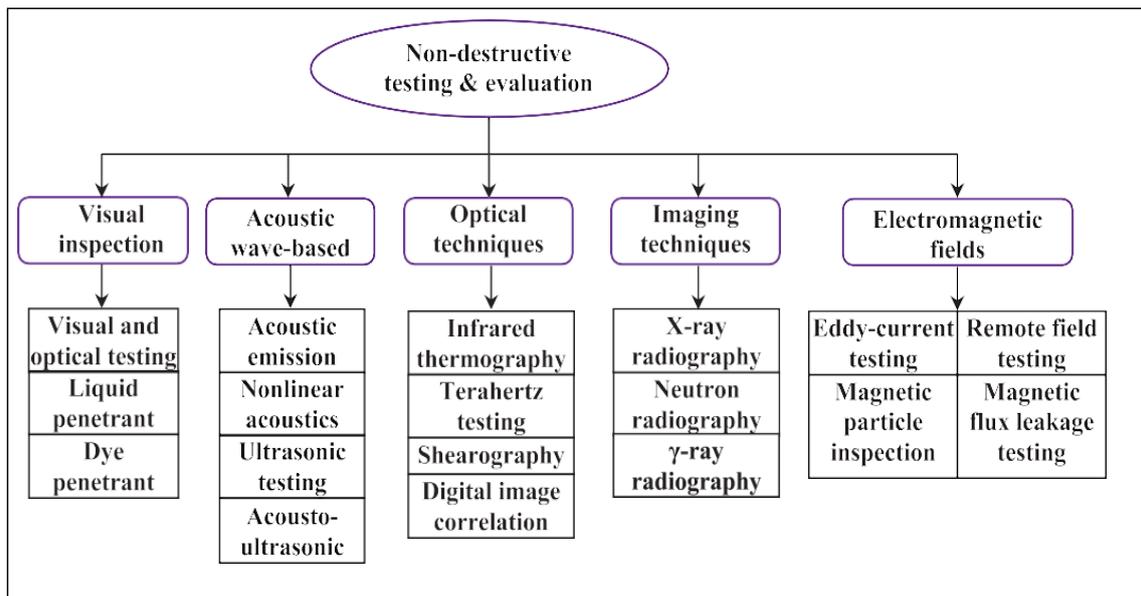

Figure 1 – Categories of non-destructive testing and evaluation techniques [5]

METHOD

Literature Review Strategy. The authors conducted a comprehensive literature search across multiple scientific databases, including ResearchGate, IEEE Xplore, ScienceDirect, and Google Scholar. The search was performed using targeted keywords such as "Non-Destructive Testing (NDT) in pipelines," "pipeline integrity assessment," "ultrasonic testing," "electromagnetic inspection," and "predictive maintenance." The inclusion criteria focused on peer-reviewed articles published between 2020 and 2024, ensuring the review captures the most current trends and developments in the field. Articles were selected based on relevance, methodological rigour, and contribution to understanding advanced NDT techniques.

Table 1 – Review of Relevant Literature

References	Objectives	Methods	Results	Findings
[6]	Improve stability and safety of energy pipeline transportation systems. Effectively detect pipeline corrosion for regular maintenance.	Electromagnetic ultrasound technology for pipeline corrosion detection. Empirical mode decomposition and singular spectrum analysis for signal denoising	Maximum wall thickness calculation error: 0.1906 mm Effective detection of pipeline corrosion and minor area defects	Non-destructive testing detects pipeline corrosion effectively. The maximum wall thickness calculation error is 0.1906 mm.

References	Objectives	Methods	Results	Findings
[7]	Application of ultrasonic-guided wave technology in corrosion detection. Review of NDT technology advancements and prospects.	Ultrasonic-guided wave non-destructive testing principles Lamb wave and shear horizontal wave mode selection	Achieved 98% accuracy in corrosion detection. Estimated approximate age of corroded pipeline	Ultrasonic-guided wave technology aids in corrosion defect detection. Advances in NDT technology include transducers and machine learning.
[8]	Enhance the quality of underwater images for corrosion detection. Estimate corrosion age using the oddy test.	Enhanced image quality algorithm for underwater images Convolution neural network for corrosion rate categorisation	A comprehensive review of ultrasonic guided wave techniques Valuable references for pipeline defect detection research	The algorithm enhances underwater image quality for corrosion detection. Achieved 98% accuracy in estimating corrosion age.
[9]	Review applications of ultrasonic-guided wave techniques in pipelines. Provide references for researchers in pipeline detection.	Developments in ultrasonic-guided wave theory Advances in transducers for detection. Signal processing techniques for monitoring.	DL-enabled FEA shows high accuracy and lower training cost. Enhances accuracy and efficiency of SCC prediction	Review of ultrasonic guided wave techniques for pipeline defect detection. Advances in theory, transducers, and signal processing techniques discussed
[10]	Review deep learning-enabled finite element analysis for SCC prediction. Investigate current research directions and applications of integrated methodologies.	Deep learning-enabled finite element analysis (DL-enabled FEA) Integration of DL algorithms with FEA	Automated non-destructive testing enhances structural health monitoring. Data transfer enables effective repair and retrofit planning.	DL and FEA are robust prediction tools with high accuracy. DL-enabled FEA enhances the accuracy and efficiency of SCC prediction.
[11]	Assess the integrity of metal structures non-destructively. Optimise repair and retrofit operations through data evaluation.	Non-destructive testing by portable devices Data transfer through virtual networks for evaluation and processing	Reliability of predictions from small sampling sizes combining experiments and simulations. Significance of methodology for evaluating current properties of exercised pipelines	Automated non-destructive testing enhances structural health monitoring. Data transfer enables effective repair and retrofit planning.
[12]	Overview of non-destructive testing procedures for pipeline steels. Assess the reliability of predictions using small sampling sizes.	Hardness and instrumented indentation tests Experimental information and numerical simulations combined for predictions	The study investigates various NDT methods for pipeline inspection. The review discusses challenges and trends in pipeline inspection and data management.	Overview of non-destructive testing procedures for pipeline steels. The reliability of predictions from small sampling sizes discussed
[13]	Investigate various non-destructive testing methods for pipelines. Compare Pipeline Inspection Gauge and robotic inspection	Magnetic flux leakage (MFL) testing Ultrasonic testing (UT) Electromagnetic acoustic technology (EMAT) Eddy current testing (EC)	The paper outlines different techniques for detecting pipeline defects. The stationary wavelet transform method is presented	The study investigates various NDT methods for pipeline inspection The review discusses challenges and trends in

References	Objectives	Methods	Results	Findings
	systems.		for structural health monitoring.	pipeline inspection and data management.
[14]	Study defect and weld integrity in pipelines. Compare electromagnetic NDT techniques on mechanical properties.	Eddy Current Testing (ECT) Eddy Current Pulsed Thermography (ECPT) Magnetic Barkhausen Noise (MBN)	ECT and ECPT yield similar results for weld properties. The detection capabilities of the methods complement those of different test pieces.	ECT and ECPT yield similar results for weld properties. The detection capabilities of the methods complement those of different test pieces.
[15]	Outline pipeline failures and their safety impacts. Study non-destructive testing techniques for leakage detection.	Visual detection, fluid odorant, mass balance, real-time transient model-based, pressure deviation, supervisory control and data acquisition system, pipeline hydro test, magnetic and ultrasonic pipe detection, acoustic emission inspection and monitoring system, wave warning system, pulse-echo flaw detector, acoustic wave reflectometry, stationary wavelet transform method	ECT and ECPT yield similar results for weld properties. The detection capabilities of the methods complement those of different test pieces.	Outlines pipeline failures' safety and environmental impacts Reviews various non-destructive testing techniques for detection

RESULTS AND DISCUSSIONS

Overview of NDT Techniques for Pipeline Integrity Assessment. The advancements in non-destructive testing (NDT) techniques have significantly enhanced the ability to assess pipeline integrity without interrupting operations. Each NDT method has unique principles and applications, making them suitable for pipeline conditions and defect types. This section discusses the various NDT techniques in detail, focusing on their principles, accuracy, cost-effectiveness, sensitivity, ease of use, speed of detection, and applicability.

Table 2 − Overview of NDT Techniques for Pipeline Integrity Assessment

NDT Technique	Principles	Accuracy	Cost-effectiveness	Sensitivity	Ease of Use	Speed of Detection	Applicability
Ultrasonic Testing [16]	Utilises high-frequency sound waves to detect internal flaws in pipeline materials.	High: Detects minor defects with detailed information	Moderate: Equipment costs vary and require skilled operators.	High: Effective for detecting internal cracks and defects.	Requires skilled operators; surface preparation is needed.	Fast: Provides immediate real-time results.	Versatile: Applicable to various pipeline materials.
Electromagnetic Inspection [2]	It employs magnetic fields to identify material discontinuities that effectively detect corrosion.	Moderate: Sensitive to corrosion but limited to conductive materials.	Cost-effective for large-scale inspections.	Moderate: Effective for external corrosion detection.	Easy: Minimal surface preparation required.	Fast: Rapid assessment of large sections.	Limited: Only effective on ferromagnetic materials.
Radiographic Testing [16]	It uses X-rays or gamma rays to produce images of internal pipeline structures.	High: Produces detailed visual images of defects.	Expensive: Requires specialised equipment and safety protocols.	High: Capable of detecting cracks, voids, and hidden defects.	Requires trained personnel and safety precautions	Slow: Set-up and analysis take considerable time.	Versatile: Effective in various environments, including offshore.
Acoustic Emission Testing [17].	Monitors stress waves generated by active defects, allowing for	Moderate: Sensitive to active defects, but external noise can	Moderate: Requires specialised equipment for	High: Effective for real-time monitoring	Complex: Data interpretation requires skilled personnel.	Real-time: Continuous monitoring of defects.	Moderate: Best for pipelines under operational

NDT Technique	Principles	Accuracy	Cost-effectiveness	Sensitivity	Ease of Use	Speed of Detection	Applicability
	real-time monitoring.	interfere.	continuous monitoring.	of crack growth.			stress.
Smart Pigging [18]	Involving inspection tools (pigs) travelling through the pipeline to collect data.	High: Comprehensive assessment of pipeline health.	High: Expensive to deploy but provides thorough inspections.	High: Detects wall thickness variations and anomalies.	Easy to use but requires pipeline accessibility.	Moderate: Depends on pipeline length and pigging speed.	High: Effective in buried and large pipelines.

The above table highlights the strengths and limitations of various methods, including ultrasonic testing (UT), electromagnetic inspection (EMI), radiographic testing (RT), acoustic emission testing (AET), and intelligent pigging. UT is highly sensitive and versatile but requires surface preparation and skilled operators. EMI provides fast assessments with minimal surface preparation but is limited to conductive materials. RT offers detailed visual records but poses health risks and is time-consuming. AET enables real-time monitoring but requires complex data interpretation. Smart pigging provides comprehensive data but has high costs and limitations in complex pipeline geometries. A comparative analysis emphasises the need to select NDT methods based on specific pipeline conditions. Integrating AI, machine learning, and IoT into NDT practices further enhances predictive maintenance and real-time monitoring, paving the way for more efficient and proactive pipeline management.
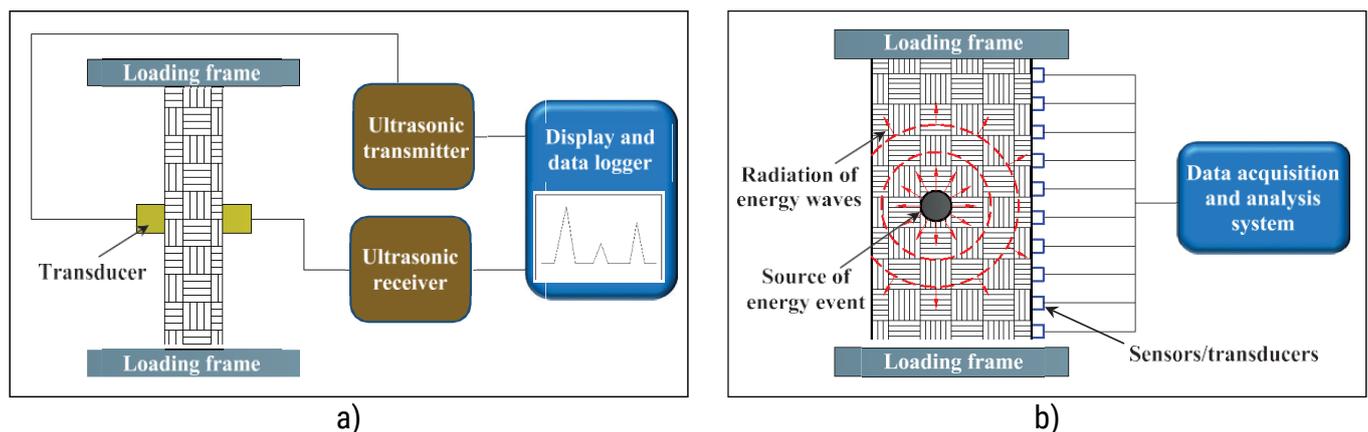

Figure 2 – a) Principle of ultrasonic testing a composite material in transmission mode;
b)Schematic of localised transient changes in stored elastic energy within a material system under loading, showing the measuring principle of the acoustic emission-based NDT technique [5]
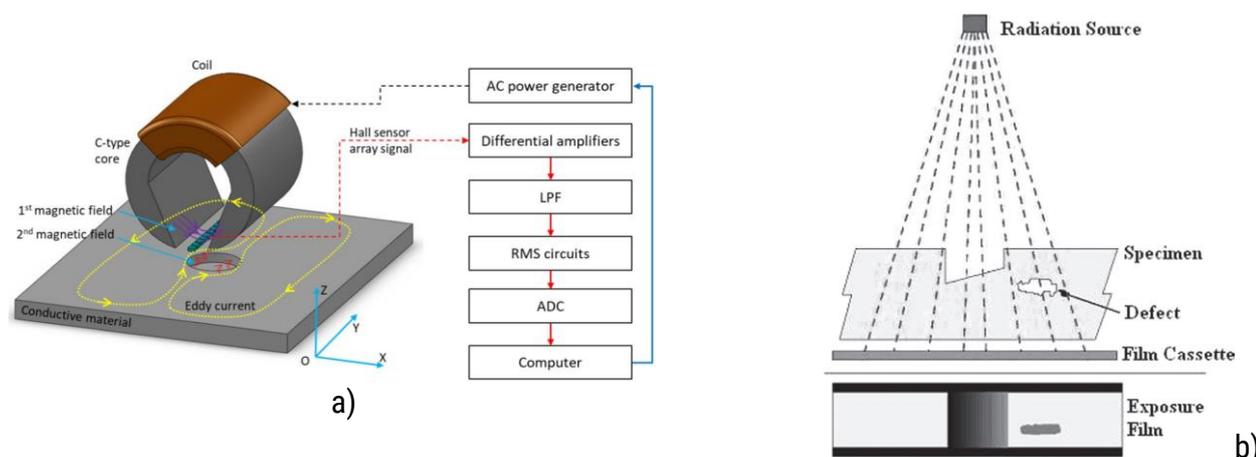

Figure 3 – a) Principle of the magnetic sensor array probe with a single magnetic source [19]; b)Working principle of the radiographic test [20]
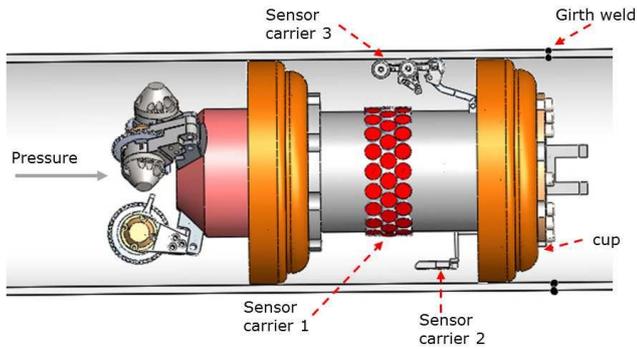
Figure 4 – Pipeline inspection gauge capsule with different types of sensor carriers mounted [21]

Overview of Pipeline Environments. Pipelines operate under diverse conditions, including varying temperatures, pressures, and environmental factors. Understanding the unique characteristics of each pipeline environment is crucial for selecting the appropriate non-destructive testing (NDT) technique. This section examines how different NDT methods are applied across various pipeline environments, including aboveground, buried, offshore, and high-temperature/high-pressure systems.

Table 3 – NDT Techniques

Pipeline Environment	Challenges	NDT Techniques
Aboveground Pipelines [9]	-Exposed to UV radiation, temperature fluctuations, and mechanical stresses. - Prone to external corrosion and material fatigue.	-Ultrasonic Testing (UT): Detects internal flaws and early corrosion. -Electromagnetic Inspection (EMI): Detects external corrosion in damaged coatings. -Acoustic Emission Testing (AET): Real-time monitoring in high-stress areas.
Buried Pipelines [22]	-Soil-induced corrosion, mechanical loading, and limited accessibility. - Difficulty in accessing pipelines for inspection.	-Smart Pigging: Inspects wall thickness and detects anomalies without excavation. -(EMI): Adapted for corrosion detection under insulation/coatings. -Ground Penetrating Radar (GPR): Maps pipelines and detects corrosion-related anomalies.
Offshore Pipelines [4]	- Subject to saltwater corrosion, pressure variations, and potential marine impacts. - Dynamic environment adds complexity to inspections.	-Ultrasonic Testing (UT): Inspects welds and joints in critical areas. -Radiographic Testing (RT): Assesses weld quality in construction phases. -ROVs with NDT Capabilities: Underwater visual and ultrasonic inspection.
HT/HP Pipeline [23]	- Extreme temperatures and pressures affect NDT performance. - Material degradation, such as creep and fatigue, is a significant concern.	-Radiographic Testing (RT): Evaluates weld integrity in high-stress areas. -Acoustic Emission Testing (AET): Real-time defect monitoring in high-stress areas. -Specialized Ultrasonic Testing (UT): Uses high-temperature resistant transducers.

CONCLUSIONS

This review has highlighted the critical role of advanced non-destructive testing (NDT) techniques in ensuring the integrity and safety of pipeline networks across diverse environments. Ultrasonic testing, electromagnetic inspection, radiographic testing, acoustic emission testing, and intelligent pigging have been shown to offer distinct advantages depending on the specific challenges posed by aboveground, buried, offshore, and high-temperature/high-pressure pipelines. Emerging technologies such as AI and IoT are also revolutionising NDT, enabling real-time monitoring and predictive maintenance. However, effectively implementing these techniques requires a tailored approach based on environmental conditions and pipeline materials. Continued research into enhancing NDT methods' accuracy, cost-effectiveness, and ease of use will be crucial for further improving pipeline safety and reliability.

REFERENCES

1. Vishnuvardhan, S., Murthy, A. R., & Choudhary, A. (2022). A review of pipeline failures, defects in pipelines and their assessment and fatigue life prediction methods. *International Journal of Pressure Vessels and Piping, 201,* 104853. doi: 10.1016/j.ijpvp.2022.104853

2. Hassani, S., & Dackermann, U. (2023). A Systematic Review of Advanced Sensor Technologies for Non-Destructive Testing and Structural Health Monitoring. *Sensors, 23*(4), 2204. doi: 10.3390/s23042204

3. Patel, R. (2022). A review on Non-Destructive Testing (NDT) Techniques: Advances, Researches and Applicability. *International Journal of Current Science Research and Review, 05*(04). doi: 10.47191/ijcsrr/v5-i4-59

4. Ho, M., El-Borgi, S., Patil, D., & Song, G. (2019). Inspection and monitoring systems subsea pipelines: A review paper. *Structural Health Monitoring, 19*(2), 606–645. doi: 10.1177/1475921719837718

5. Wang, B., Zhong, S., Lee, T., Fancey, K. S., & Mi, J. (2020). Non-destructive testing and evaluation of composite materials/structures: A state-of-the-art review. *Advances in Mechanical Engineering, 12*(4), 168781402091376. doi: 10.1177/1687814020913761

6. Tian, Y., Palaev, A. G., Shammazov, I. A., & Ren, Y. (2024). Non-destructive testing technology for corrosion wall thickness reduction defects in pipelines based on electromagnetic ultrasound. *Frontiers in Earth Science, 12.* doi: 10.3389/feart.2024.1432043

7. Lyu, F., Zhou, X., Ding, Z., Qiao, X., & Song, D. (2024). Application Research of Ultrasonic-Guided Wave Technology in Pipeline Corrosion Defect Detection: A review. *Coatings, 14*(3), 358. doi: 10.3390/coatings14030358

8. Inbavalli, A., Shanmugasundaram, B., & Chozhavendan, S. (2023). Non-Invasive Submerged Pipeline Inspection Through Advanced Image Analysis and Deep Learning Algorithms for Quantitative Deterioration Assessment. *2023 3rd International Conference on Pervasive Computing and Social Networking (ICPCSN), 15*, 193–198. doi: 10.1109/icpcsn58827.2023.00037

9. Zang, X., Xu, Z., Lu, H., Zhu, C., & Zhang, Z. (2023). Ultrasonic guided wave techniques and applications in pipeline defect detection: A review. *International Journal of Pressure Vessels and Piping, 206,* 105033. doi: 10.1016/j.ijpvp.2023.105033

10. Sarwar, U., Mokhtar, A. A., Muhammad, M., Wassan, R. K., Soomro, A. A., Wassan, M. A., & Kaka, S. (2024). Enhancing pipeline integrity: a comprehensive review of deep learning-enabled finite element analysis for stress corrosion cracking prediction. *Engineering Applications of Computational Fluid Mechanics, 18*(1). doi: 10.1080/19942060.2024.2302906

11. Bolzon, G. (2022). Automated non-destructive integrity assessment of metal structures. *Procedia Structural Integrity, 41*, 9–13. doi: 10.1016/j.prostr.2022.05.003

12. Bolzon, G. (2020). Non-destructive mechanical testing of pipelines. In *Lecture notes in civil engineering* (pp. 3–14). doi: 10.1007/978-3-030-58073-5_1

13. Ma, Q., Tian, G., Zeng, Y., Li, R., Song, H., Wang, Z., Gao, B., & Zeng, K. (2021). Pipeline In-Line Inspection Method, Instrumentation and Data Management. *Sensors, 21*(11), 3862. doi: 10.3390/s21113862

14. Ma, Q. P., Tian, G. Y., Gao, B., Bajic, D., Culafic, S., Liu, J., Wu, T., Zeng, K., Liu, Z., Liu, Q., Yang, C., & Liu, D. (2020). Comparison of pipeline welds and integrity through different electromagnetic NDT techniques. *Conference: 2020 IEEE International Instrumentation and Measurement Technology Conference (I2MTC)* (pp. 1-6)

15. Razvarz, S., Jafari, R., & Gegov, A. (2020). A review of different pipeline defect detection techniques. *Studies in Systems, Decision and Control*, 25–57. doi: 10.1007/978-3-030-59246-2_2

16. Gupta, M., Khan, M. A., Butola, R., & Singari, R. M. (2021). Advances in applications of Non-Destructive Testing (NDT): A review. *Advances in Materials and Processing Technologies, 8*(2), 2286–2307. doi: 10.1080/2374068x.2021.1909332

17. He, Y., Li, M., Meng, Z., Chen, S., Huang, S., Hu, Y., & Zou, X. (2020). An overview of acoustic emission inspection and monitoring technology in the key components of renewable energy systems. *Mechanical Systems and Signal Processing, 148,* 107146. doi: 10.1016/j.ymssp.2020.107146

18. Guan, L., Cong, X., Zhang, Q., Liu, F., Gao, Y., An, W., & Noureldin, A. (2020). A Comprehensive Review of Micro-Inertial Measurement Unit-Based Intelligent PIG Multi-Sensor Fusion Technologies for Small-Diameter Pipeline surveying. *Micromachines, 11*(9), 840. doi: 10.3390/mi11090840

19. Le, M., Luong, V. S., Nguyen, K. D., & Lee, J. (2021). Electromagnetic testing of corrosion at rivet sites via principal component analysis. *Journal of Non-destructive Evaluation, 40*(2). doi: 10.1007/s10921-021-00768-8

20. Taskin, M., Elazig, U. C., & Turkmen, M. (2011). X-ray tests of AISI 430 and 304 Stainless Steels and AISI 1010 Low Carbon Steel Welded by CO2 Laser beam welding. *Materials Testing, 53*(11–12), 741–747. doi: 10.3139/120.110283

21. Ramirez-Martinez, A., Rodríguez-Olivares, N. A., Torres-Torres, S., Ronquillo-Lomelí, G., & Soto-Cajiga, J. A. (2019). Design and validation of an articulated sensor carrier to improve the automatic pipeline inspection. *Sensors, 19*(6), 1394. doi: 10.3390/s19061394

22. Chen, P., Li, R., Jia, G., Lan, H., Fu, K., & Liu, X. (2023). A Decade Review of the Art of Inspection and Monitoring Technologies for Long-Distance Oil and Gas Pipelines in Permafrost Areas. *Energies, 16*(4), 1751. doi: 10.3390/en16041751

23. Wright, R. F., Lu, P., Devkota, J., Lu, F., Ziomek-Moroz, M., & Ohodnicki, P. R. (2019). Corrosion Sensors for Structural Health Monitoring of Oil and Natural Gas Infrastructure: A review. *Sensors, 19*(18), 3964. doi: 10.3390/s19183964