EMERGING TECHNOLOGIES IN NON-DESTRUCTIVE TESTING: SMART SENSORS, DRONES, AI AND AUGMENTED REALITY

Ph.D. Eng. Rodica DAVID,
Constantin Brâncuși University from Târgu Jiu, Romania
Student Ioana-Cristina DAVID,
Technical University of Civil Engineering of Bucharest, Romania
Faculty of Civil, Industrial and Agricultural Buildings

Abstract: Non-Destructive Testing (NDT) constitutes a fundamental domain within modern industrial processes, serving to ensure the safety and integrity of materials, equipment, and structures without compromising their operational functionality. In the contemporary context of global digitalization and automation, traditional NDT methodologies are increasingly being complemented, or in some cases replaced, by solutions with emerging technologies, including smart sensors, autonomous drone-based inspection systems, and augmented reality (AR).
These technological innovations not only enhance the efficiency and accuracy of inspection procedures but also enable a predictive maintenance approach, transforming NDT from a reactive, post-factum verification activity into a continuous, real-time process of monitoring and analyzing structural and operational conditions. In this way, the article presents the contributions of these emerging technologies to the advancement of non-destructive testing, providing applications and highlighting potential directions for future research.

KEY WORDS: non-destructive testing, inspection procedures, smart sensors, augmented reality.

INTRODUCTION

In an era where digitalization and automation are redefining industrial processes, non-destructive testing (NDT) remains a crucial domain for ensuring the safety, quality, and reliability of materials and structures. From critical infrastructure, energy equipment to aircraft and industrial components, NDT plays a decisive role in preventing accidents and reducing maintenance costs.

Non-destructive testing encompasses a range of methods and techniques that allow the assessment of the structural integrity of semi-finished products, components, or equipment without affecting their functionality or usability. It represents an essential element at all stages of the production process, with the primary objectives of ensuring product reliability, preventing defects and accidents, and enhancing profitability.

Moreover, NDT techniques are also applied during periodic inspections of in-service components or equipment to evaluate both structural integrity and operational safety. Although the implementation of one or more NDT techniques may be costly and increase production expenses, the benefits are reflected in what is often termed "intangible profit." A product that operates without defects over an extended period enhances customer satisfaction and contributes to the manufacturer's reputation and net profit.

Traditionally, NDT methods have relied on techniques such as ultrasonics, radiography, or magnetic testing, which provide accurate results but are often costly and time-consuming. In today's context, marked by the development of intelligent technologies, these methods are being complemented by digital tools capable of continuous monitoring, automated data analysis, and real-time decision support. For this, three major directions emerge: smart sensors, which enable predictive monitoring of equipment, drones, which provide safe and rapid access to hard-to-reach areas and augmented reality, which facilitates assisted inspection and technician training. The integration of these emerging technologies contributes to transforming NDT into a digitalized, interconnected, and sustainable process. [1]

1. EQUIPMENT AND APPLICATIONS DESIGNED FOR NON-DESTRUCTIVE TESTING

For the efficient implementation of nondestructive testing (NDT), selecting the appropriate equipment and identifying the corresponding applications are essential steps. Modern NDT techniques rely on a wide range of tools and technologies, from smart sensors and thermographic cameras to drones equipped with LiDAR (Light Detection and Ranging) systems and specialized data analysis software. Each type of equipment is designed to meet specific requirements, such as structural monitoring, detection of hidden defects, or assessment of the operational safety. Moreover, the practical applications of these technologies span multiple industrial sectors – from infrastructure and energy to the aerospace industry and the production of critical components. [2]

Correctly selecting and integrating equipment with the suitable applications allows for the optimization of inspection processes, reduction of time and associated costs and an increased operational safety for the workers.

1.1. Smart sensors – the foundation of predictive monitoring

Smart sensors represent one of the most significant technological advancements in the field of nondestructive testing (NDT). They combine measurement capabilities with data processing, communication, and self-diagnosis functions. By integrating them into Internet of Things (IoT) systems, it is possible to achieve continuous, real-time monitoring of the condition of materials and structures.

In industrial applications, smart sensors can be used to detect abnormal vibrations, monitor temperature, pressure, or structural deformations. For example, in the aerospace industry, networks of sensors integrated into aircraft wings allow the identification of microcracks before they become critical. In civil engineering, tension and vibration sensors monitor the behavior of structures during earthquakes or load variations.

Another significant aspect is the integration of artificial intelligence (AI) algorithms in the analysis of sensor data. This enables the recognition of degradation patterns and the implementation of predictive maintenance strategies. Consequently, smart sensors contribute to reducing maintenance costs and increasing the service life of industrial equipment.

1.2. Drones – fast, safe, and autonomous for inspections

The use of drones in nondestructive testing (NDT) has expanded significantly over the last decade 2015-2025, particularly in areas where human access is difficult or dangerous. Equipped with multispectral cameras, ultrasonic sensors, thermographic devices, or LiDAR systems, drones can collect detailed data about the condition of structures without requiring facility shutdowns.

LiDAR is a remote sensing technology that uses laser pulses to determine distances between a sensor and objects in the environment. In short, a LiDAR system emits thousands or even millions of laser pulses per second toward a surface. The time it takes for each pulse to travel from emission to return to the sensor (after reflecting off the object) is measured with extreme precision. Based on these measurements, the system calculates distances and creates a three-dimensional (3D) model of the environment. [3]

The main components of a LiDAR System are: the laser source – emits short light pulses, usually in the infrared range, the detection sensor (photodetector) – captures light reflected from objects, the time-of-flight (ToF) measurement system – calculates the time between pulse emission and reception, the navigation unit (GPS + IMU) determines the exact position and orientation of the sensor, essential for accurate 3D model reconstruction and the processing software generates a 3D point cloud and converts it into models, maps or precise measurements.

In this way, the LiDAR System can produce nondestructive testing and industrial inspections, measuring deformations, identifying cracks, or detecting corrosion, can monitories the stability of structures or material volumes in construction and infrastructure.

It provides high-precision 3D measurements (up to a few millimeters), works effectively over large or complex surfaces, can be mounted on drones, vehicles, satellites, or portable instruments.

Nevertheless, it presents limitations, such as:

- performance decreases in rain, fog, or dusty conditions;
- costs that can be very high;
- requires specialized software and experts for data processing.

In the energy sector, drones are used to inspect wind turbines, high-voltage lines, and gas pipelines. They can detect cracks, corrosion, or insulation losses, helping to prevent major incidents. In construction, drones facilitate visual assessments of, reducing inspection time by up to 70% compared to traditional methods. Current trends focus on the development of fully autonomous drones capable of planning and executing inspection missions without direct human intervention. Combined with AI-based automated image analysis, these systems can generate detailed reports on structural integrity, contributing to the standardization of NDT processes. Additionally, advances in real-time data processing and cloud-based analytics facilitate immediate feedback and predictive maintenance, reducing downtime and enhancing the overall efficiency of infrastructure monitoring programs.

2. AUGMENTED REALITY – AN ADVANCED INTERFACE FOR INSPECTION AND MAINTENANCE

Augmented Reality (AR) provides a bridge between the physical and digital environments, allowing operators to visualize relevant information directly overlaid on the real objects being inspected. In the context of nondestructive testing (NDT), this technology is used to assist inspections, training, and decision-making.

AR also facilitates remote collaboration between operators and experts, reducing the time required for diagnosing and repairing faults.

Current research focuses on integrating AR with digital twins, allowing comparison between a virtual model of equipment and its real-time condition. This approach opens promising perspectives for implementing NDT in critical industries such as nuclear, aerospace, and energy sectors. [4]

Here are some concrete examples of how augmented reality (AR) is applied in inspection and maintenance:

a) real-time sensor data (temperature, vibration, pressure) on machines, allow engineers to quickly identify abnormal readings without manual checks;
b) field engineers can stream their AR view to a remote expert, who can annotate the technician’s view in real time, guiding them through complex repairs;
c) can provide step-by-step instructions for disassembling, inspecting, and reassembling equipment, reducing errors;
d) overlays schematics or maintenance histories onto pipelines or powerlines during drone inspections, helping engineers spot corrosion, leaks, or damaged components more efficiently.
e) helps mechanics visualize internal components of engines or aircraft systems without disassembly, highlighting parts that need inspection or replacement;

f) highlights potential safety hazards or regulatory compliance points directly on equipment, ensuring inspections meet standards without needing extensive manuals.

AR in NDT can be summarized as in the following flowchart:

REAL-WORLD OBJECT
(product, machinery, component to be inspected)

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AUGMENTED REALITY (AR)
(provides digital info, potential defects, guides inspectors step-by-step)

↓

DEFECT DETECTION & ANALYSIS
(identifies cracks, faults or inconsistencies, provides real-time feedback)

↓

REPORTING & IMPROVEMENT
(logs defects automatically, suggests corrective actions, enhances quality control)

Augmented reality (AR) is transforming the way industrial inspections and maintenance are performed by overlaying digital information directly onto physical assets. Through AR interfaces, technicians can visualize real-time data, receive step-by-step guidance, and identify potential issues without interrupting operations. This not only improves accuracy and efficiency but also reduces human error, training time, and operational downtime. By integrating AR with smart sensors and predictive analytics, maintenance and inspection processes become more intuitive, data-driven, and proactive. [5, 6, 7]

CONCLUSION

Apart from the traditional techniques for examining the defects, techniques that are still used, like: Magnetic Testing (MT), Radiographic Testing (RT), Visual testing (VT), Thermographic testing (TT), Leak testing (LT), the adoption of smart sensors, drones, and augmented reality represents a digital revolution in non-destructive testing. These technologies not only enhance precision and efficiency but also fundament-tally reshape the design of maintenance and quality assurance programs.

Looking ahead, the integration of these solutions with AI and machine-learning driven analytics platforms is set to enable fully autonomous monitoring and inspection systems, capable of predicting and preventing failures before they occur. As a result, NDT evolves from a simple verification method into a strategic instrument for the sustainable management of non-destructing testing procedures. [8]

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