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DEVELOPMENT OF AN OPEN-SOURCE ROBOTIC NDT SOLUTION FOR AUTOMATED COMPOSITE REPAIR TESTING

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Abstract

Non-destructive testing (NDT) plays an important role in aircraft maintenance and repair processes, ensuring the structural integrity necessary for safe operation. The paper presents the design and evaluation of an animated, low-cost robotic NDT system tailored for inspecting composite bonding agents. The system integrates commercially available components, including a three-degree-of-freedom robotic arm and a Raspberry Pi 4B, managed by custom Python software with a user-friendly graphical interface. Mechanical Impedance Analysis (MIA) and Eddy Current Testing (ET) methods were employed to assess the system's performance on representative test specimens. Results indicate that the system delivers reliable and accurate measurements comparable to commercial tools like the MAUS V, while offering simplicity and modularity. Limitations such as scanning speed and handling of complex geometries are acknowledged, with potential solutions proposed for future enhancement. The system provides an affordable and customizable alternative for NDT automation in the aerospace industry.

Keywords: non-destructive testing, robotics, automation, Eddy Current Testing, Mechanical Impedance Analysis, Python, airworthiness
Article category: research article

INTRODUCTION

Aircraft requires periodic inspections in accordance with procedures developed by manufacturers and approved by the competent aviation authorities. During such inspections, damages caused by fatigue, corrosion or incidents are detected and, in most cases, these damages are repaired according to procedures. Often, composite repairs are made.

According to recommendations (Morozov et al., 2018), NDT methods are used to confirm the quality of repairs. The most commonly used method of performing NDT inspection is the manual A-scan. Manual testing results in many inconsistencies, such as variations in probe angle and pressing force. These factors may lead to non-repeatable, less reliable results.

Automation of such tests offers improvements in their precision and speed (Govindaraju & Palanisamy, 2018; Morozov et al., 2018), provides more informative data, and reduces costs by minimizing service time. There are many different approaches to automation systems, varying in the operation concepts and their use cases, with the most common (Buckley et al., 2003; Morozov et al., 2018; *Invert robotics adding NDT tech to mobile climbing robots*, 2019) being:

- Robot driving on the examined surface,
- Robot arm,
- Probe shifting along two axes (XY scanner).

Each system has some advantages over the others when operating in certain conditions. Despite their high reliability and speed, modern automated systems tend to be expensive, complex solutions with very few possibilities for future feature extensions.

This paper aims to address the above problem by designing an automated NDT system and evaluating its performance in terms of test reliability and the quality of user experience. The desired outcome can be achieved by combining features and characteristics of commercial tools and technical solutions necessary for workflow and architectural simplicity.

The task discussed by this paper has been extensively described in numerous articles. Different approaches and testing methods are chosen based on the defined user and specimen needs. Choosing the proper testing method may be crucial for acquiring correct results when examining specimens made from specific materials. Their size and geometry highly affect the necessary approach to access large areas or ones with limited exposure.

Study (Mineo et al., 2013) describes a system utilizing an automated arm with six degrees of freedom, although it tests its performance only with use of flat, simple samples. This idea is extended in (Morozov et al., 2018) by using a high precision robotic arm with six degrees of freedom and performing an examination of strongly curved part of an aircraft's wing leading edge. That paper also presents scanning path planning based on a CAD model and achieved results gained with eddy current testing method. The study reported in (Haase & Maurer, 2004) proposes two systems, adapted to large-scale inspections with the ability to move mainly along the X, Y and Z axes and to slightly adjust to the specimen's curvature. Another example is described in (Lange, 1994), which presents a significantly different approach. There, a system designed for scanning the fuselage skin is meant to access any of its areas irrespective of its orientation, hence it is configured as a climbing robot that performs ongoing scans and moves along the skin with use of a set of suction cups.

The above survey of current solutions was not focused solely on a single, most probable approach but aimed to highlight the need for adjusting it to very specific needs and to identify certain higher-level requirements for proper concept choice. These considerations lead to conclusions about the main needs the designed system has to fulfill. The designed system primarily aims to be:

- Capable of creating reliable, readable results,
- Simple and low-cost in construction,
- Made of parts generally available on the market,
- Equipped with open software, enabling users to expand its functionality and use different testing methods,
- Simple and intuitive to use,

In the testing phase, the project utilizes two NDT methods:

- Mechanical Impedance Analysis (MIA):

The method, used to detect delaminations in composites, metals and bonded structures (Lange, 1994), is based on measurements of harmonic force input by a probe at a point on a surface and the resultant velocity of this point (Cawley, 1987). These values yield the impedance (Cawley, 1987; Lange, 1994).

$$Z = \frac{F}{v}$$

The method is sensitive to changes in surface stiffness, thickness, elastic properties, and density (Cawley, 1987; Lange, 1994). As long as all layers are bonded, the received signal maintains high values, dropping once a flaw is detected (Lange, 1994).

- Eddy Current Testing (ET):

This method is employed in inspecting metal structures for both surface and subsurface defects (García-Martín et al., 2011). It operates by the principle of electromagnetic induction (Kondej et al., 2017). The magnetic field induces eddy currents flow in the test sample, which create their own electromagnetic field, weakening the original one. This dependency allows for the detection of cracks by changes in the impedance signal (García-Martín et al., 2011).

It is worth noting that the two methods just described are comparative. This means for proper evaluation of results, it is necessary to compare them with those obtained for standardized sample with known and accurate characteristics.

SYSTEM CONFIGURATION

In order to fulfill the needs stated in the previous section, specific components were chosen. The system's main concept was based on robotic arm (Dobot Magician) operating in cartesian coordinate system. The arm has 3 degrees of freedom, which leads to limited compensation for geometry irregularities. To improve this, a probe with spring suspension was used. The probe signal is sent in real-time to flaw detector which translates it into a voltage signal and transits it to a Raspberry Pi 4B computer. All the hardware was managed in custom Python software developed by the present authors. To ensure ease of use, the system's control program was equipped with a Graphical User Interface (GUI) that guides user through the scanning process, enabling them to choose the proper working parameters (such as resolution, sample size, and plot type). It also post-processes the acquired data and generates plots in the desired format. The relationship between the main components of system is shown in Figure 1.

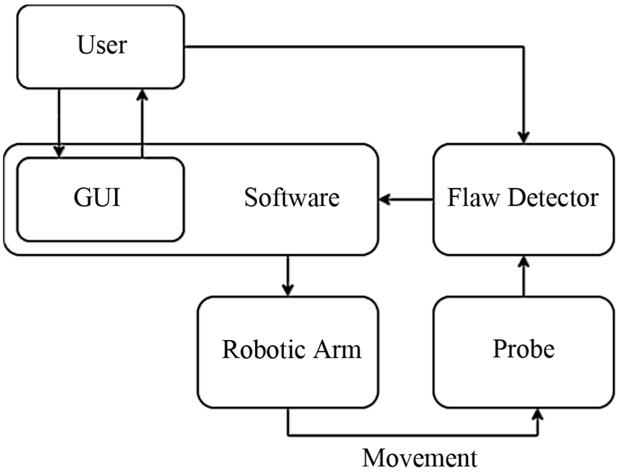


Figure 1. System diagram

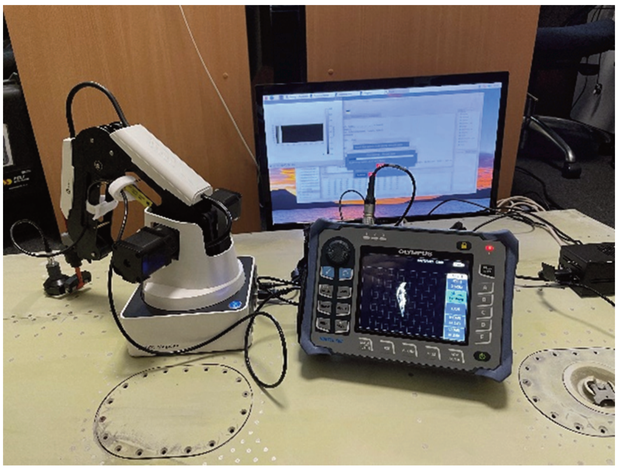


Figure 2. System assembly

The result is an open-loop system with no possibility of reducing arm movement inaccuracies. This is not seen as an issue due to the robot's decent precision, although it is also an area for future applications of closed-loop systems. Such a configuration maintains high modularity, enabling the user to replace scanner parts or extend its functionality. As flaw detectors, OLYMPUS family devices (NORTEC, BondMaster) were used. Equipped with standardized VGA connectors they made it possible to acquire measurement signals. Regardless of the flaw detector, the captured signal is within a similar voltage range, which makes it easy to change the application of the system.

TESTING RESULTS

Tests of two samples were conducted. The first of these required the MIA method. Standardized sandwich sample was made of glass and carbon fiber skins with a Nomex honeycomb core. Such kind of structures are widely used in the aerospace industry, since they offer a combination of high stiffness and low mass (Wróbel et al., 2015).

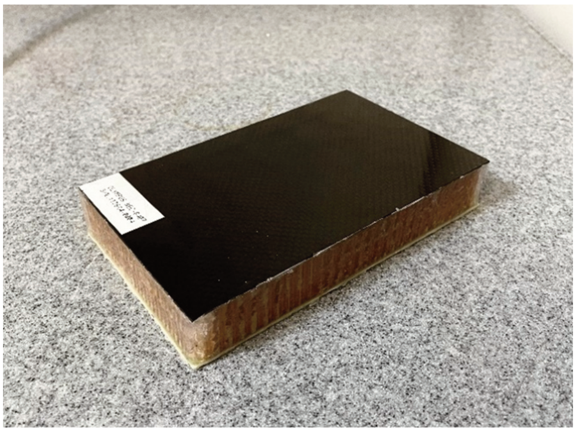


Figure 3. Sample 1. (used for MIA testing)

The collected data is visualized as C-scans. Plots are elaborated in different colors: in 2D, which is usually more legible, and in 3D, which can sometimes be more informative in certain use cases.

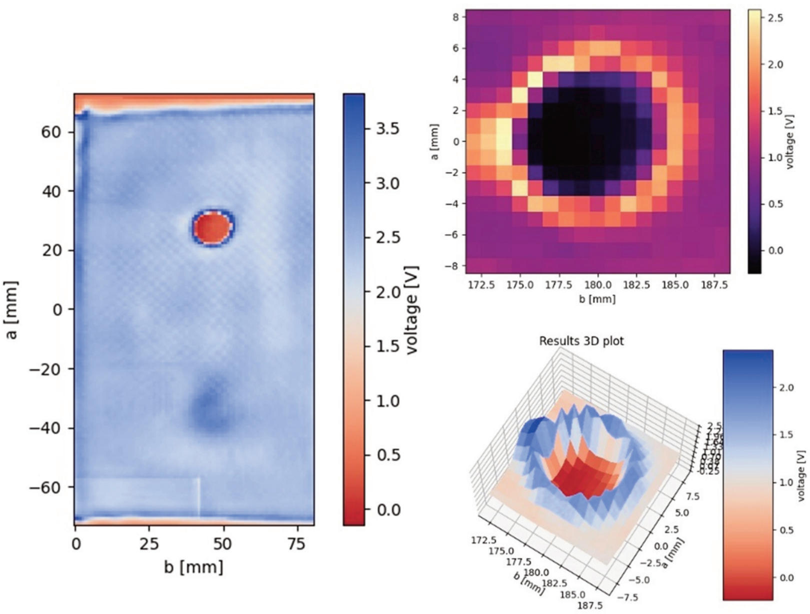


Figure 4. MIA results for sample 1.

The second sample is aluminum plate with a repair patch above the simulated cracks of different lengths. Another feature differentiating this element from previous one is its curvature, which may cause complications during scanning and printing of results on a flat surface.

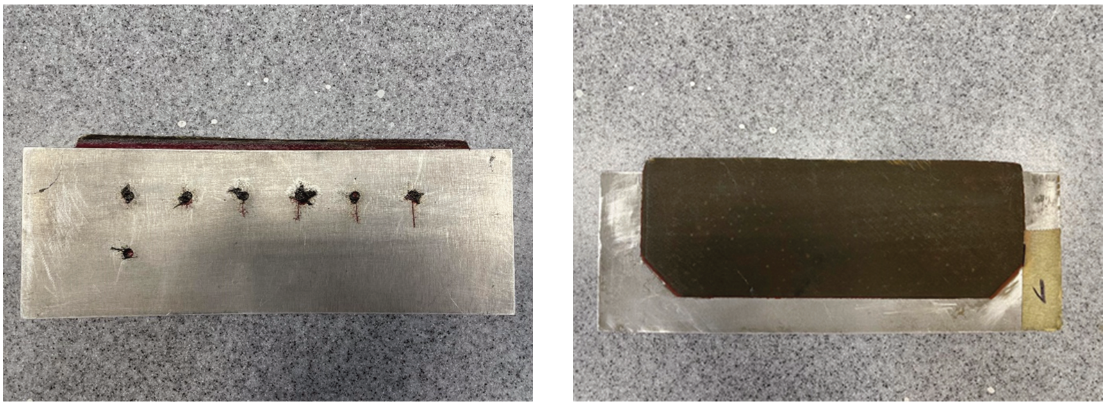


Figure 5. Sample 2. for ET testing method

The element requires the ET method for testing. The results are presented in the same way as before:

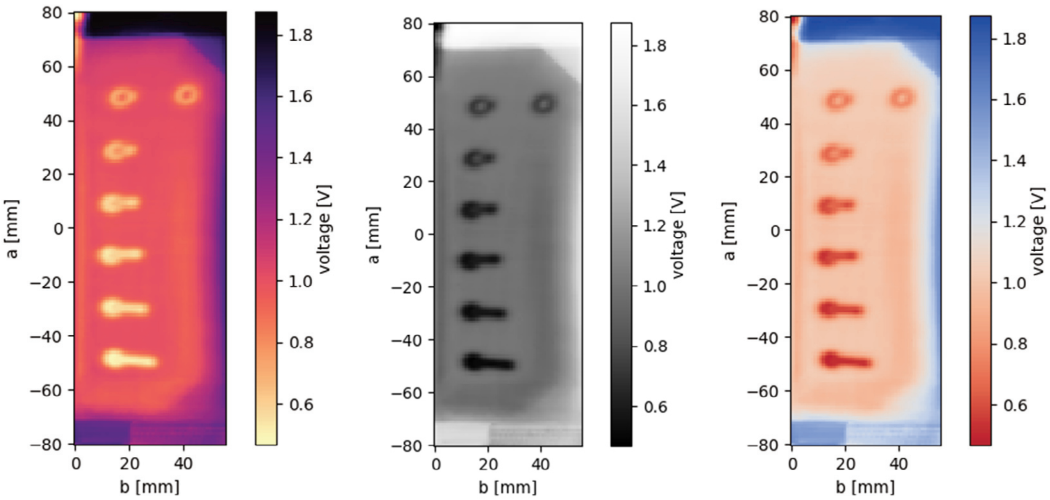
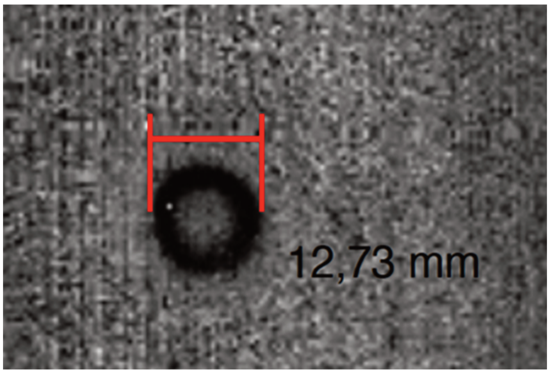


Figure 6. ET results for sample 2.

SYSTEM EVALUATION

For quantitative evaluation, numerical comparisons of the results acquired by the designed tool and commercial tool (MAUS V) were made. The scaling objects of analysis for each sample was sample 1, tested with the MIA method. For both systems, the resultant image was scaled first due to the known size of the label sticker placed on the outer surface, which made it possible to measure carbon-fiber disbond. Such a comparison is considered as reliable, since the sticker's size is manually measurable. Two plots are shown on Figure 7a and b.

a)



b)

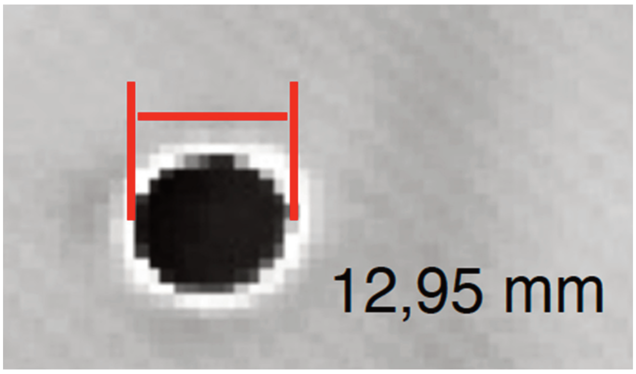


Figure 7. a) results obtained with MAUS V system,
b) results obtained with designed system

The dimension deviation is acceptably low, which confirms the reliability of the designed test system. Although an analogous analysis was not conducted for sample 2, the visible distortion indicates the presence of higher dimensions deviations for both systems.

Qualitative evaluation was based on the presented results, workflow experience and final compliance with assumptions stated in the introduction section above. All the defects on both samples are visible and hence detectable. Plots are clear and resemble those attainable with commercial scanners. Th shape for sample 1 is well preserved; however, there is image distortion for sample 2. Such plot deformation makes impossible to digitally measure any dimensions of the specimen's features, although it does not affect data readability or the ability to perform comparative analysis.

The tool is built with market accessible parts, the cost of which is relatively low, compared to commercial systems operating on a similar basis. Each part is connected in an uncomplicated way – connections are made with widely available interface, such as USB, or ones standardized for NDT testers. Workflow facilitation and improvements are provided by the software and built-in GUI.

One problem the scanner faces is low scanning speed. This issue is caused by the choice of programming language: despite being simple and proper tool for prototyping new functions. Python forces the arm to operate only one step at a time.

CONCLUSIONS

The developed robotic NDT system successfully meets the initial objectives of being modular, user-friendly, and cost-effective, while delivering reliable and accurate inspection results for composite bonded repairs. By utilizing readily available hardware components and open-source software, the system offers customization and ease of maintenance, making it a practical solution for automating NDT processes in aircraft maintenance.

Challenges such as limited scanning speed, restricted movement range, and result distortions on complex geometries were identified; however, these issues can be addressed through hardware upgrades and software enhancements due to the system's modular design.

Future work will focus on overcoming these limitations, improving performance, and expanding capabilities to handle a wider range of inspection scenarios. The proposed system represents a significant advancement toward accessible and efficient NDT automation in the aerospace industry.

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