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Review

A Comprehensive Review on Corrosion Detection Methods for Aircraft: Moving from Offline Methodologies to Real-Time Monitoring Combined with Digital Twin Technology

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Abstract: Corrosion is a pervasive issue that limits the service life of an aircraft and leads to their degradation. Timely and accurate detection and monitoring of corrosion are crucial for maintaining structural integrity and preventing catastrophic failures. This review explores various techniques for corrosion detection, including conventional and innovative Non-Destructive Inspection (NDI) methods. Another promising trend is the development of real-time corrosion sensors that enhance non-destructive testing by providing early warnings of corrosion in aircraft structures. Additionally, advancements in Artificial Intelligence (AI), Machine Learning (ML), and the concept of digital twins represent cutting-edge technologies in the realm of corrosion monitoring. This review offers a comprehensive and up-to-date overview of these approaches, highlighting the challenges and prospects of these methods. We also propose the innovative potential of integrating diverse approaches to construct a digital twin, which aims to characterize the behaviour of physical entities by leveraging a virtual replica in real time.

***Keywords*:** aircraft corrosion, non-destructive inspection, real-time sensors, artificial intelligence, digital twin

1. Introduction

Metals constitute a major part of aircraft structure despite several improvements in aircraft material selection. The selection of specific metallic materials for aircraft structures is mainly based on the properties of the metals like weight, heat resistance, stiffness, strength, electrical properties, etc. Due to their light weight and high strength, aluminium alloys are mainly used for airframe construction. Aluminium in its pristine state is very soft and not appropriate for the fabrication of structural elements. The addition of other metals to create an alloy improves its strength, workability, and corrosion resistance. Alloying of aluminium with copper is done to improve its strength. The addition of magnesium to aluminium helps in making it corrosion-resistant. Many highly stressed parts of an aircraft like the landing gear wheels, reciprocating engine pistons, etc. are usually made from aluminium alloys. They are also used to fabricate the rivets used in modern aircraft [1]. Other metals used in the aircraft industry mainly consist of stainless steel, titanium, and magnesium. These metals are particularly selected based on their specific properties. For example, stainless steel which is hardly affected by corrosion or heat is mainly used for making the leading edges of wings and in fixtures exposed to heat or erosion/corrosion attacks. Similarly, titanium with its high melting point is ideal for use in firewalls, and

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turbine-engine shrouds of high-speed aircraft where heat rise is substantial. Magnesium, like aluminium, is primarily used as airframe material because of its light weight. Though it has the maximum strength-to-weight ratio of all aircraft materials, it is very costly and burns aggressively if its ignition temperature is reached. Because of this, it can never be used in aircraft areas where temperature is high [2], [3]. Moreover, it is highly susceptible to various forms of corrosion and requires protective coatings and regular corrosion checks when used in aircraft.

In this review article, we will discuss various non-destructive inspection (NDI) techniques that are commonly used for the detection of corrosion in aircraft structures. There are very few review articles published on this topic till today [4]-[8]. Apart from the conventional and non-conventional NDI techniques for corrosion detection, we have reviewed the use of corrosion sensors in aircraft. These sensor systems work hand-in-hand with the NDI techniques to detect the onset of corrosion in hidden areas that are unreachable using NDI techniques. We discussed the possibility of using Artificial Intelligence (AI) based techniques for corrosion detection and lifetime predictions for aircraft. Finally, we have proposed the idea of creating a digital twin model of the physical conditions of the aircraft structure by integrating the inspection techniques for complete and faster corrosion monitoring and detection.

1.1 *Corrosion in aircraft structures*

An aircraft during its flight is exposed to various conditions that are favourable for causing corrosion in the metallic structures. The paint of an aircraft can be damaged by the materials on the runway, such as stones, gravel, and de-icing salts. This can explore the metal structure below and make it susceptible to corrosion. This is more likely to happen when an aircraft takes off or lands. In the same way, aircraft are also exposed to oils, fluids, and fuel during operation, scrapes and scratches from maintenance works, accidental damages, exhaust gases, etc. Maritime aircraft suffer from salt attack, which is one of the most severe corrosion factors.

There has been a lot of work carried out on corrosion-resistant materials. However, these materials could rarely find application in aircraft structures because the strength-to-weight ratio of the materials is a more wanted property than corrosion resistance for aircraft. In cases like this, corrosion can be controlled only by taking preventive measures which usually involve the use of a coating or paint that acts as a barrier to the environment. Despite a lot of protective measures taken, corrosion still occurs at a slow pace and leads to catastrophic failures, if unnoticed [3], [9].

Aircraft structures can experience different types of corrosion, for example, uniform corrosion, pitting corrosion, intergranular corrosion, crevice corrosion, galvanic corrosion, stress corrosion, hydrogen embrittlement, fatigue corrosion, erosion corrosion, etc. [10]. Uniform corrosion is the most common type of corrosion, which is a uniform deterioration of the surface without appreciable localized attack, resulting in uniform surface thinning. Pitting corrosion is a major confined type of corrosion, in which pits grow in a material resulting in the contained damage of the metal. Pitting corrosion occurs when one part of a metal turns out to be anodic compared to the rest of the material. The pits formed from pitting corrosion are generally very tiny and therefore, difficult to notice during routine examination in the initial stages. Another form of localized corrosion which is severe near the junctions of dissimilar metals and less affected farther from the junction is galvanic corrosion. It is a result of poor material selection and bad design.

Crevice corrosion happens when fluctuations in the corrosive atmosphere occur and lead to faster localized attack. This phenomenon usually occurs when narrow crevices are present in the structure that contains a stationary environment. This results in the concentration change of the corrosive electrolyte in the crevice region and the surrounding surface of the metal. Crevices are generally formed at joints between two metals or a metal/non-metallic contact, or a deposit of debris on the metal surface which can act as starting point for corrosion. Stress and fatigue corrosion are caused by the simultaneous effect of various types of stress and environmental factors. The stress causing the failure usually originates during in-operation conditions or from residual stress in the components accumulated during the manufacturing process. Hydrogen embrittlement is a failure process that occurs when a metal under applied or residual stress absorbs or retains hydrogen. This type of failure is most common in high-strength steels [5], [11].

1.2 *Cost of corrosion and corrosion management*

Corrosion incurs a significant economic impact. For instance, in the fiscal year of 2017, corrosion cost the Aviation and Missiles section of the US Department of Defence was US $8.97 billion, and this rose to US $10.18 billion in FY2018. The US Air Force spent US $5.67 billion on corrosion in FY2018, which was 23.6% of its total maintenance costs [12], [13]. Apart from the safety point, corrosion management is also important from the economic point of view. According to the Federal Aviation Administration (FAA) of the United States, more than 30% of maintenance costs in aircraft of the Air Force and Navy comes from fixing various forms of structural corrosion [14]. Furthermore, it was reported that 10 to 25% of structural failures in aircraft leading to accidents are caused by corrosion, which makes the problem significant and still current [15], [16]. Frequent inspections and maintenance routines are required for aircraft to detect accumulated corrosion damage over the service life which is a potential risk to the safety of the flight.

In the present scenario, Schedule-Based Maintenance (SBM) is adopted for the inspection of corrosion in aircraft, in which the aircraft is inspected for maintenance activities on a scheduled basis [17]. The current SBM is often insufficient for detecting and monitoring corrosion, which is a major factor in the high cost of corrosion management. Various non-destructive inspection techniques, such as visual inspection, ultrasound, eddy current and others, are used regularly to inspect corrosion [7]. Corrosion damage is measured by these methods through the loss of mass, the formation of oxide, and the presence of structural defects such as deformation due to strain, erosion, cracks, and coating deterioration. But each of these common inspection techniques have their own pros and cons. For example, visual inspection lacks reliability since it mostly fails to identify corrosion in hidden and confined sites like the crevice corrosion. Corrosion detection and monitoring in SBM is often inadequate and costly. Conventional methods and devices, such as corrosion coupons, electrical resistance and ultrasonic sensors, have limited coverage and electronic issues that require frequent maintenance and replacement. They can estimate corrosion rate and location, but not the type, source or condition of corrosion. Moreover, in SBM, corrosion data is only available during scheduled maintenance, which may be too late for prevention or repair. The maintenance/replacement of corroded parts also causes longer downtime and higher cost. Corrosion rejection criteria for components and systems are determined case by case to ensure aircraft safety [18].

Recently, there has been effort towards Condition Based Maintenance (CBM) approach for aircraft mainly to reduce costs, detect and monitor corrosion in-time, thus ensuring better aircraft safety [5]. In this approach, statistical tools are used to perform probabilistic-based prognostics and health management approaches for maintenance procedures. This method to detect and to monitor corrosion is expected to provide a more efficient and less expensive corrosion management strategy. The main requirement for this approach is an on-board corrosion sensing system. The system will provide information regarding corrosion state and corrosion rates for corrosion prognostics. The advance indications help to lessen safety risks, improve asset management, and decrease maintenance costs of aircraft. The use of corrosion sensor can also help in the replacement of hazardous, chrome-based primers (for corrosion protection) with chrome-free alternatives on aircraft [19]. To evaluate how well the coating system protects against corrosion in different service environments for a specific fleet, data from corrosion sensors can be collected and analysed either on the ground or on-board. Such data could offer the fleet-specific information based on aircraft usage for the development of new maintenance strategies to reduce cost without compromising structural integrity of the aircraft [7], [20].

1.3 *Major aircraft accidents due to corrosion*

Corrosion has led to many catastrophic accidents in the past. In a study by Findlay and Harrison, it was found that corrosion in aircraft parts is the cause of about a quarter of the major aircraft failures [16]. Below we discuss a few of major aircraft accidents in the past that have resulted in loss of human life, the reasons for which have been identified as unnoticed corrosion.

In 1988, the upper part of a Boeing 737 in service at Aloha Airlines was separated. The reason for this accident was ascribed to dis-bonding, corrosion, and cracking problems. Even though corrosion was noticed as per the maintenance record before the incident, it was accepted as a normal operating condition and no maintenance activities were undertaken. It was found that the "pillowing" phenomenon caused by the build-up of substantial corrosion products between the lap joints, resulted in the separation of the faying surfaces [21]-[22]. The Aloha Airlines accident was the initiator of the recommendations for corrosion prevention and control program in the aviation industry [23].

A second incident is the crash of MiG 23 aircraft in the Kortijk cottage (1989) in the base in Bagicz (near Kołobrzeg in Poland). The catastrophic accident was due to the engine failure caused by electrochemical corrosion in the engine control system mainly from the marine environment in which the flight was operating. It remained unnoticed during the inspections. This case is an example that the corrosion can occur in unseen places or elements and a routine maintenance inspection may not help in identifying such corrosions [24].

In 2016, the incident of Zen Air CH-601HD aircraft in which the wheel from the right landing gear separated from the plane during the run before take-off was also identified because of unnoticed corrosion. Corrosion had penetrated in more than 25% of the weld reducing the strength of the joint. The corrosion was hidden from standard visual inspection and could have been identified only through specific detection techniques or sensors [24].

During the year 2013, the right engine of an Airbus A330 aircraft running at the airport in Manchester caught fire and the investigation showed the turbine blade had developed a fracture which was initiated by pitting corrosion. The accident could have been prevented if corrosion had been detected in the earlier stage [25].

1.4 *Need for early corrosion detection*

A lot of research has being carried out for protecting the aircraft structure and preventing the various forms of corrosion [8], [18], [26]-[28]. Corrosion prevention measures generally include surface treatments like anodization, corrosion-prohibiting primers, corrosion inhibitors as well as protective coatings. However, corrosion cannot be prevented completely using such measures. The aircraft structure needs regular checking and upkeep to detect corrosion, as it faces various corrosive factors during operation. These include moisture and pollutants, salt spray in sea areas or sulphate ions in cities, fluids for cleaning and de-icing, and so on [18]. Additionally, erosion corrosion can happen from sand and dust, impact from gravel, hail stones, etc. [29]. The structural integrity of an aircraft is affected if corrosion remains undetected or left unaddressed [30]. In the most severe cases, corrosion can cause catastrophic structural failure. So, there is a pressing need to develop such novel materials that can improve the resistance of material towards corrosion and also have an efficient corrosion detection system which can notify the onset of corrosion in critical areas so that major accidents can be avoided [31], [32]. Kumar et al. experimentally found that adding approximately 0.1-0.2 wt.% of Sn significantly improves the localized corrosion resistance of stainless steels [33]. A study on stainless steel and aluminum also revealed that the erosion rate is directly proportional to bulk hardness [34]. In order to resolve the issues with corrosion it is important to primarily understand the corrosion parameters. Figure 1 depicts a corrosion matrix chart that consists of three categories of corrosion sensing and detection, namely, physical, environmental, and chemical parameters.

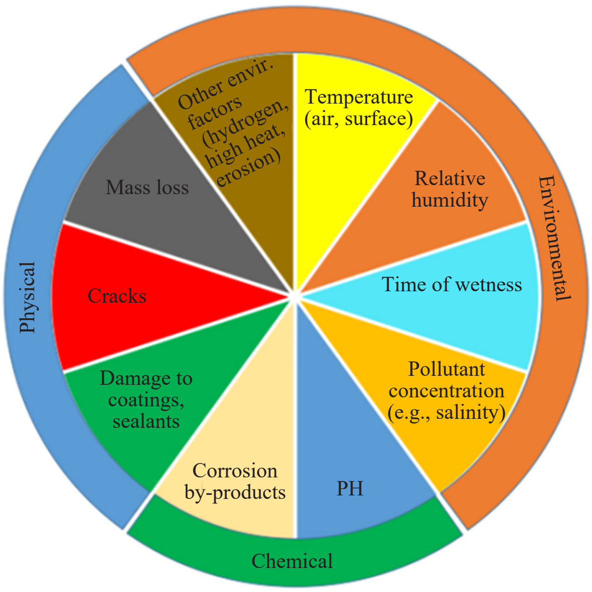

Figure 1. Corrosion matrix of physical, chemical, and environmental factors [7]

The physical parameters of corrosion like cracks, mass loss and damage to coatings, etc. are often detected using NDI techniques like visual inspection, enhanced visual NDI like D-sight, ultrasonic, eddy current, thermography, radiography, and other NDI methods as discussed in detail in the sections below. Structural health monitoring (SHM) techniques like acoustic emission and optical fibre sensors can also help to identify these physical parameters of corrosion. The key environmental factors leading to corrosion are temperature, relative humidity, pollutants like sea slats, acidic electrolytes, and atmospheric pollutants like SO_2, NH_3, etc. The rate and the intensity of corrosion vary according to the concentration, frequency, and exposure time of these parameters. Various corrosion environmental sensors can be used to collect information on these and correlate them to the location, time, and rates of corrosion. The details of these sensor systems are discussed in detail in the following sessions. Other factors such as changes in pH and corrosion by-products are also direct indicators of corrosion [35]. The growth of machine learning (ML) techniques like support vector machines and decision trees (DT) and deep learning (DL) techniques like convolutional neural networks, recurrent neural networks, and autoencoders have provided notable advancements in efficiently detecting cracks and corrosion. Recently, Shams et al. have reviewed exhaustively how these latest techniques are revolutionising the traditional methods of crack and corrosion detection at an early stage and with more accuracy [36].

There are several effective methods for detecting corrosion in aircraft, each with its advantages and disadvantages. These techniques vary in their approach, sensitivity, and applicability to different types of structures and corrosion scenarios.

Proactive and effective corrosion sensing/monitoring for aircraft typically requires complementary data across three key areas: physical, environmental, and chemical corrosion parameters as described in the pert chart in Figure 1. This dataset can be used to assess the corrosion environment, determine the severity and rate of corrosion, and subsequently integrate this information into an aircraft's damage tolerance model or incorporated into a digital twin. There are studies where corrosion detection systems have been categorised based on physical, chemical, and environmental factors [37]. However, the current priority is to identify a more reliable and precise method for implementing corrosion monitoring by accurately pinpointing the areas being assessed. Therefore here we have innovatively categorised the corrosion detection methods based on the area to be monitored, like the NDI techniques involve studying a larger inspection area, whereas a sensor can be employed in a very specific and targeted area. On the other hand sensor system forms a network that continuously monitors multiple locations across the aircraft,

The various detection methods are illustrated in the flowchart below in Figure 2 and are discussed in detail in the following sections of this review.

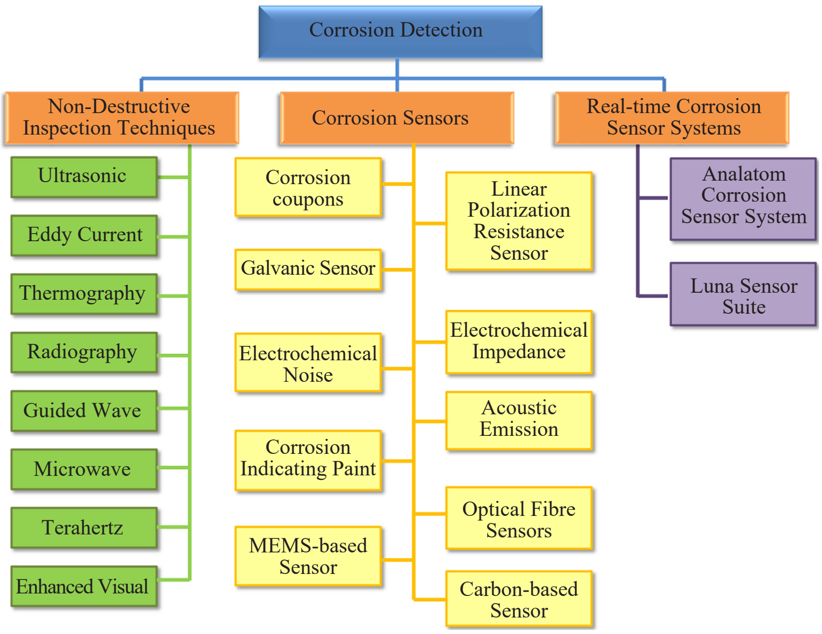

Figure 2. Classification of different corrosion detection techniques

2. NDI techniques for corrosion detection in aircraft

Detecting corrosion at the right time is of utmost importance in the battle against corrosion. There are many non-intrusive and indirect testing methods to identify corrosion in aircraft structures. These approaches can detect corrosion without the need to directly interfere with the structure. A few of the most common NDI techniques are discussed below:

2.1 *Ultrasonic method*

Ultrasonic waves are highly sensitive to structural damage and can penetrate materials making them suitable for corrosion detection [38]. The material under inspection is scanned with high-frequency sound waves to find out its internal structure, thickness, and other characteristics in the corrosion monitoring process. The instruments designed for corrosion measurements using the Ultrasonic method generally identify corrosion from the transition time between the first and back wall echo and calculate the time difference between the successive echoes. This method can be very convenient for measuring the thickness of metals for the detection of pits and cracks [39]-[41]. Ultrasonic testing is considered one of the most promising NDI techniques for measuring the thickness of corrosion and the remaining material thickness, as the acoustic properties of the base material and the corrosion layer are different. The technique can also be used to determine the thickness of hollow components and detect internal corrosion by in-depth penetration of ultrasonic waves [1], [40], [42]. However, this pulse-echo method is not suitable for early-stage corrosion detection due to poor resolution [43]. Liu et al. developed high-frequency ultrasonic non-destructive testing (NDT) techniques, including piezoelectric pulse-echo and laser-ultrasonic methods, for detecting corrosion in nickel superalloys. These methods have shown the capability to measure corrosion layer thicknesses of around 100 µm. However, when a multilayer corrosion structure forms over time, these ultrasonic techniques can generally only detect the thickness of the outermost corrosion layer. This limitation occurs because the varying mechanical properties across the different layers create acoustic contrasts that hinder the detection of the deeper layers [44]. Real corrosion on the back surface of an aircraft aluminum structure was also detected with a thickness loss of 5% (0.1 mm in a 2-mm plate) using ultrasonic technique. This method identifies changes in surface roughness caused by corrosion rather than material loss or thinning of the plate, making it especially effective for early corrosion detection [45].

2.1.1 *Laser ultrasonic*

In recent times, laser-based ultrasound techniques have been extensively applied for defect visualization in various applications. Lasers are used to create and sense ultrasound in this advanced ultrasonic method. It has become a promising modality for corrosion inspection in aircraft structures because of its several advantages like non-contact generation and detection, need for little to no surface preparation, detection independent of the surface orientation, and capability of testing under harsh conditions like high temperature and pressure [46].

In this non-contact technique for corrosion detection, lasers have been used to generate and detect ultrasonic waves for detecting material thickness and flaws with high precision [39], [47]. Laser-ultrasonics can quickly and accurately find hidden corrosion in the overlapping parts of aircraft [39], [48]. A lap joint consists of at least two metallic parts joined together using fasteners. Corrosion at the lap joints leads to thinning of the metallic parts and bulging of the lap joints because of the accumulation of the corrosion products. If the thinning of the metals goes below a specific level (normally 10% of the actual thickness), the lap joint must be replaced to avoid failures [39]. Monitoring lap joint corrosion is a tedious, time-consuming task, which is normally carried out through visual inspection by observing the bulging in the joints with a beam of light at a grazing angle to the joint. Laser-based ultrasonics helps to overcome these difficulties and is considered a prime candidate for automated detection of hidden corrosion in lap joints [31]. A study published by the Industrial Materials Institute (IMI), National Research Council of Canada, showed that this method could easily detect metal loss of less than 1% and showed the same level of accuracy as X-ray images, without dismantling the system [48]. Here, the ultrasonic waves generated by the laser interact with the corrosion products, and the subsequent changes observed in the wave nodes are detected using time-frequency analysis techniques without disturbing the structure. The major drawback of this method is that access to the surface of the object under test is required for detection [39].

2.2 *Eddy current test method*

Eddy current test (ET) method allows the non-destructive inspection of materials on a surface and near-surface level [49]. In this method, AC is applied to a conductive coil kept close to the object, in response to which the test object will generate eddy currents. ET can also be used for crack detection. Detailed scrutinization of small-scale cracks is possible by using currents with lower penetration depths at high frequencies, thereby, increasing the phase differential between defects and making them easily identifiable. On the other hand, low frequencies increase depth penetration but experience poor sensitivity.

Fitzpatrick et al. [50] in their study showed that most of the surface-breaking fatigue cracks in aluminium can be imaged at eddy current frequencies of 25.6-102.4 kHz. Hidden multilayer cracks and corrosion can be identified through imaging at lower frequencies. The capabilities and limitations of transient eddy currents for the detection of corrosion and cracks in aluminium alloys up to a depth of 11 mm were studied by Smith et al. [51]. In the reported study, 0.09 mm of metal loss at a depth of 7 mm and 0.01 mm of metal loss at a 1.5-mm depth could be identified with high precision using the ET technique. However, at a depth of 11 mm a significant metal loss of up to 0.5 mm was just detectable. The overall effectiveness of the technique reduces at deeper penetration depths because of the signal quality. This is the major disadvantage of ET over other NDI techniques [51], [52].

Bohacova [53] developed a novel methodology for conducting eddy current (EC) inspections in critical areas of wing spars, motivated by a catastrophic glider accident in 2010 that led to a suspension of all glider services. The area of focus was located within the wing spar structure, which was composed of six layers. Specifically, the critical zone was situated beneath the countersunk rivet head in the third layer of the spar flange, concealed by two additional layers of metal sheets. As a result, the critical area itself lies within the fourth layer, directly beneath the rivet. To address the challenges posed by this hidden area, he designed a specialized eddy current probe capable of operating within a frequency range of 200 Hz to 100 kHz, which allowed single-value interpretation of individual EC signals, thereby, enhancing the accuracy and reliability of inspections in these critical regions. Another study focused on the detection of cracks located in the third layer of aircraft structures, particularly at rivet sites, utilizing eddy currents induced by a giant magneto-resistive (GMR) sensor system [54]. The developed system was proficient in identifying cracks as small as 1 mm deep within a material up to 10 mm below the surface.

By leveraging the sensitivity of GMR sensors to changes in magnetic fields generated by eddy currents, one can achieve precise detection of structural integrity issues, significantly enhancing maintenance and safety protocols in aviation. This innovative approach promises to improve the reliability of inspections in critical areas, ensuring early identification of potential failures.

Compared to the conventional eddy current system, pulsed eddy current (PEC) systems reduce the inspection time and simplify the information interpretation time because of their ability to capture broadband frequency information within a single transient signal [55].

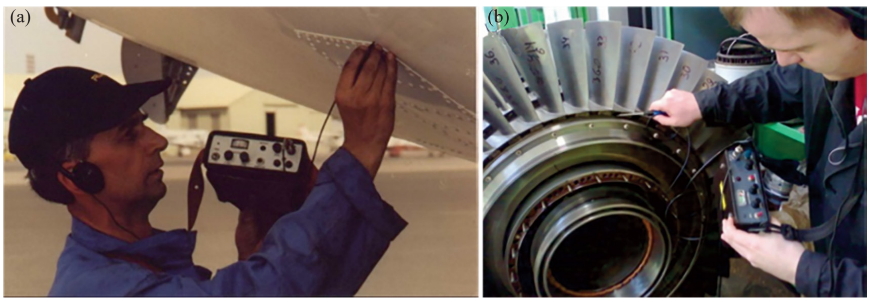

Figure 3. Inspection of (a) AN-12 aircraft fuselage and (b) engine components by the VD3.03 type Eddy Current flow detector [55]

PEC thermography showed promising results for the detection of corrosion under insulation (CUI) in aircraft structures [56]. In a report [56], Hernandez et al. defects ranging from 0.4 mm to 5 mm in a painted corroded aluminium sample were identified using PECT. Figure 3 shows the inspection of an aircraft fuselage and engine parts using the eddy current detector.

2.3 *Thermography*

The thermography technique uses a camera with many infrared sensors to detect and measure small temperature differences. In general, there are two types of thermography techniques-passive thermography and active thermography [57]. In passive thermography, the camera is pointed at a test piece, and a temperature map is constructed from the thermal image. In active thermography, the surface of the object is heated quickly using an external heat source, and the falloff in temperature with time is observed. Flaws in the material are shown by differences in the temperature decline rate. Hidden corrosion manifests itself mostly by creating solid oxide compounds, which exhibit a different thermal profile as compared to uncorroded surfaces, hence making their detection possible [56], [58].

The thermography inspection technique has demonstrated its capability to reveal hidden damage under the surface of aircraft wing skins, caused by corrosion spreading around the holes where fasteners are inserted [58]. In the presence of water/moisture the interaction between steel fastener and aluminium skin results in exfoliation corrosion which grows parallel to the skin surface but is invisible from the surface and hence not easily detectable.

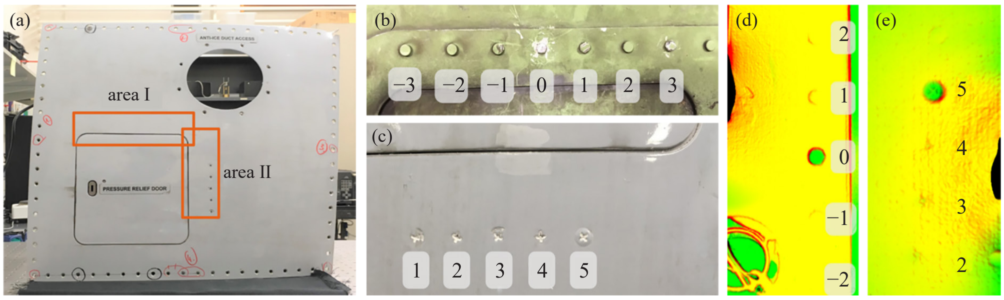

Figure 4. (a) Areas of a fuselage panel from an AIRBUS A320 aircraft with modified rivets (b) Area I-back (c) Area II-front (d) The measurement of area I (rotated by 90°) with the IPHWT and (e) IPHWT of area II [52]

In-plane heatwave thermography (IPHWT) can be employed for the digital inspection of fasteners in aircraft fuselage panels [59]. This technique displays the viability to detect and measure the quality of rivets and screws in aluminium aircraft fuselage based on thermal irregularities in the thermographic images obtained as shown in Figure 4. In a recent study by Thilakarathna et al. [60] an automated thermographic inspection system based on IR thermography has been used to detect surface coating defects on aircraft fuselage. The system gives a signal when a defect or corrosion is detected while imaging.

2.4 *Radiography method*

Historically, radiography was the most used NDI method for corrosion detection. Radiography uses short-wave electromagnetic beams, like *X*-rays or *γ*-rays from radioactive isotopes with high energy sufficient to penetrate solid materials. As the beam passes through the material, some energy is absorbed depending on its thickness. Therefore, the intensity of the transmitted beam varies with the thickness of the material. If a photographic film is placed behind the test specimen, the areas behind the thin parts of the specimen will be darkened because the transmitted beam intensity was high, while the light behind the thick parts will be brightened due to the low intensity of the transmitted light, i.e., pits and thinning of the material will be visible as dark regions. The main disadvantage of radiography is the difficulty in detecting narrow cracks if they are oriented in directions other than parallel to the beam [61]-[63].

In a study, Dunn et al. [64] through both simulation and laboratory experimentation, demonstrated that the X-ray backscatter technique effectively detects internal flaws, such as hidden corrosion, disbonding, and voids in samples representative of actual aircraft. This radiography technique offers several advantages over competing NDI methods as it can be implemented without requiring subjective image analysis and is easily automated. Additionally, the probability of detection (POD) can be fine-tuned by adjusting a single parameter: the figure-of-merit cut-off value. Their findings indicated that this limited-scan backscatter technique can reliably identify as little as 5% material loss at depths of up to 0.508 cm (0.200 in.) and 10% material loss at depths of up to 0.635 cm (0.250 in.) beneath aircraft skin surfaces. Hydrogen-rich materials can be detected well by Neutron Radiography (NRad) because hydrogen absorbs a lot of neutrons [65]. Hence, it is used in the aircraft industry to detect corrosion [66]. NRad can be used to detect corrosion in aluminium by analysing the corrosion products, which mainly consist of various Al-salts, oxides, bayerite, etc. [67]. The effectiveness of the radiography technique depends heavily on the thickness and composition of the corrosion products [68].

2.5 *Guided wave*

Guided waves have been widely explored for corrosion and crack detection in aircraft structures. Guided wave detection technique has certain advantages like rapid screening, in-service inspection, low cost, etc. The phase velocity and the frequency of the guided wave can be tuned to make the detection simple and straight-forward. It has been found that guided wave is very helpful in detecting fuselage wall thinning, debonding of lap splice joints, debonding of skin to core, etc. in aircraft [31], [40], [67]. Gao et al. [31] used a technique based on multi-frequency wavenumber estimation to calculate the size, location, and depth of corrosion in aircraft. The studies showed that the speed of the guided wave changes when it passes through the corroded area. The size and depth of the corrosion can be measured accurately by using a special technique that analyses the wavefield at a single mode with different frequencies. This technique is called the multi-frequency local wavenumber method and it uses a short window in the space domain to perform a Fourier transform. High-frequency guided waves can also be used in monitoring the corrosion thickness loss [69].

2.5.1 *Microwave NDI*

Microwave NDI is a very effective method of detecting corrosion in paint or coating. Due to high frequencies, microwaves (in the frequency range 300 MHz to 300 GHz) can easily penetrate through the coatings without much attenuation, unlike ultrasonic waves. Microwave testing has been in use since the early 1950s, but recent years have seen a surge in interest and advancements in the field. Notable milestones include the formation of a dedicated microwave testing committee by the American Society for Non-Destructive Testing (ASNT) in 2014 and the establishment of a user group by the British Institute of Non-Destructive Testing (BINDT) in 2015. In 2016, ASNT officially recognized microwave testing as a distinct non-destructive testing (NDT) method. The following year, Boeing launched a laboratory focused on employing microwave technology for the non-destructive detection of flaws in coatings and structures [70]. Various microwave sensors have been employed in corrosion testing applications, including open-ended waveguides [71], coaxial lines, planar resonators [72], and open cavity resonators [73]. For instance, open-ended waveguides are often used for their ability to probe material properties, while coaxial lines provide robust measurements in confined spaces. Planar resonators and open cavity resonators are also valuable, offering high sensitivity and precision in detecting flaws.

Microwave NDI methods present several key advantages for the detection and assessment of corrosion under coatings. Microwaves can penetrate low-loss dielectric materials, allowing for interaction with their internal structures. They exhibit sensitivity to variations in dielectric properties and boundary interfaces, rendering them particularly effective for identifying unwanted layers, such as corrosion beneath the paint. These microwave techniques are characterized by their non-contact, one-sided (reflection) nature, and are recognized for their rapid, straightforward implementation. Additionally, microwave measurement systems are compact, easily integrated with commercially available scanning and imaging mechanisms, and possess portability, robustness, and battery-operated functionality, often in handheld configurations. Recent advancements in near-field microwave NDI techniques, utilizing open-ended rectangular waveguide probes, have successfully facilitated the detection of corrosion products beneath paint and primer on both steel and aluminium substrates [74], [75]. Moreover, these techniques have shown efficacy in identifying and evaluating corrosion precursor pitting under coatings, attributed to their high spatial resolution.

Microwave inspection can be conducted in two modes: reflection mode and transmission mode. In reflection mode, the microwave signal is transmitted through the inspected material and then reflected back for analysis [76].

Microwave NDI technique was used to detect corrosion in steel on concrete up to 500 mm [15]. A wide range of applications of microwave NDI for corrosion detection, especially pitting corrosion in insulated steel and aluminium are available [77]. Microwave NDI can also be used to detect the presence of water in corrosion layers, water being the main cause of corrosion [78]. Since microwaves cannot effectively pass through conducting surfaces, they cannot be used for detecting subsurface corrosion [75]. Gray et al. [79] designed a robotic platform for automated inspection that utilizes a combination of infrared thermography and phased array ultrasonics to assess near-surface and subsurface damage. The robot employs a vortex-based actuation system, allowing it to adhere to the inspected surface. Additionally, it is capable of transporting inspection and repair tools to the relevant areas.

2.6 *Terahertz technology*

The development and application of terahertz sources and advanced testing equipment have unlocked the potential of terahertz technology for detecting non-conductive materials, offering unique advantages in the non-destructive testing of composites. Terahertz radiation (THz) offers a non-invasive, non-contact, non-ionizing method and unique characteristics for non-destructive evaluation compared to other forms of electromagnetic radiation. While microwaves can penetrate composites, their spatial resolution is limited due to longer wavelengths. Infrared techniques provide better spatial resolution than terahertz but have less penetration depth. In contrast, terahertz (THz) radiation can non-invasively penetrate composites with submillimeter transverse resolution, allowing for the detection of surface defects, hidden voids, delaminations, and bending damage. Moreover, the depth resolution for defects is significantly better than the spatial resolution, enabling effective analysis of thin composite samples using THz time-domain spectroscopy (TDS). During the manufacturing process, quality-assurance inspections of the thin sheets of aircraft can be conducted using a transmissive THz system, as the sheets are thin enough to allow THz transmission and are unobstructed by structural components. However, for inspections conducted after the aircraft has been manufactured, reflective THz geometry is necessary, as structural components beneath the layer of interest often obstruct the penetration of transmitted THz waves [80]. Terahertz (THz) waves are electromagnetic waves with wavelengths in the range of 0.03 mm to 3 mm and with frequencies between 0.1 and 10 THz. In the THz technology, a wave of known wavelength is used to light the surface being studied [81]. The inner structure or corrosion in the surface is determined by analysing the changes in the THz signal because any defects or corrosion in the surface will affect the signal. The use of THz technology for the detection of corrosion under coating has been demonstrated by NASA [82] and U.S. Military Research Laboratory [83]. Stoik et al. [84] identified puncture holes, localized burn damage, and areas of paint or composite removal of glass fiber composite samples provided by the Air Force Research Laboratory Materials and Manufacturing Directorate at Wright-Patterson AFB, OH using THz technology. The study demonstrated the material properties of glass fiber composites using reflection geometry, along with imaging of damaged samples. In a study, Zhong et al. [85] showed that effective terahertz imaging technology enables the accurate distinction of low-velocity impact damage defects in carbon-fiber-reinforced composite laminates across the 0.12-2.0 THz frequency range. Also, by analyzing terahertz time- and frequency-domain signals, along with amplitude differences and local eigenvalue imaging, qualitative detection of low-velocity impact damage in experimental specimens can be attained. Nicoletti et al. [86] also demonstrated the significant potential to use THz time-domain spectroscopy (THz-TDS) to sense degradation in multilayer paint coatings in aircraft. The major disadvantage of THz technology is its high cost and inability to penetrate through metallic surfaces, thus limiting its application.

2.7 *Enhanced visual NDI techniques*

In recent times, novel NDI techniques have been developed for further improvement in the detection capabilities. One such technique developed is the enhanced visual NDI technique [87]. It is useful to find surface topographical information like dents, cracks, corrosion pillowing, or other irregularities in the aircraft surface. In comparison to the traditional NDI approaches, these enhanced visual NDIs have better speed and ease of inspection and interpretation. These techniques are also less expensive compared to the conventional NDI methods. The most common enhanced visual NDI methods are the D-Sight and the Edge of Light (EOL) techniques [87]. The following sections discuss these techniques.

2.7.1 *The D-Sight method*

The optical impact detection system called D-Sight was developed by Komorowski et al. [88], [89] based on the double pass retroreflection. In this technique, the structure under test is observed at an oblique angle to detect the deformations caused by corrosion. The system was further improved through the collaboration of the Canadian Department of National Defence, US Air Force, FAA, and Transport Canada with Diffracto Ltd. and NRC. The main advantage of D-Sight compared to other common NDI techniques is that it can perform inspection of a larger area at a faster rate with high sensitivity to defects [87]. Many of these systems are being used by the Air Force in the US, Canada, France, and the UK for corrosion detection in aircraft [5], [90]. A device that inspects the surface of an object, called an inspection head, is one of the main components in the D-Sight Aircraft Inspection Systems (DAIS). The other components are a camera that captures images, a light source that illuminates the object, and a computer that runs special software for planning and performing the inspection [89]. The remote pendant with touch-sensitive screen is used for controlling the acquisition process. In the DIAS system, the inspection head scans through the aircraft body to capture the D-Sight image. The acquired images are shown on the pendant touch screen. The images are analysed after completing the acquisition process for the inspected surface or complete aircraft to save time. Image analyses are carried out at a workstation and results are studied to locate the detected damage.

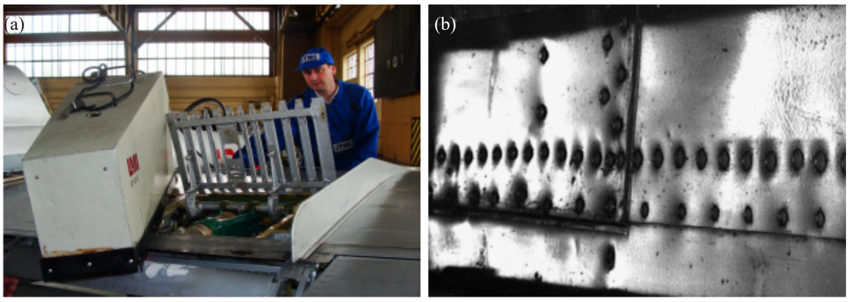

Figure 5. (a) Inspection of aircraft using DAIS 250C and (b) exemplary D-Sight image of an aircraft skin panel [27]

An example of a D-Sight image from an inspection is shown in Figure 5 (b) [27]. Due to the high sensitivity of the technique to surface deformations, it has found applications in the inspection of automotive elements and aircraft fuselage structures for corrosion and defects. The D-Sight technology has undergone a lot of improvements since its development. Numerical modelling of corrosion to support the quantification of hidden corrosion detected with the D-Sight technique and improved detection with the help of artificial intelligence (AI) have been added to the technique to enhance its performance in detecting corrosion. For instance, automated corrosion detection with high precision was developed by using deep neural networks with D-Sight [5]. In another study, deep learning techniques [91] and multi-teacher knowledge distillation [92] were used to demonstrate automatic corrosion detection from D-Sight.

2.7.2 *Edge of light (EOL) scanner*

Edge of light (EOL) is another enhanced visual NDI technique that has recently gained attention for corrosion analysis [93], [94]. An EOL scanner of a simple design employs a light source and a detector separated by a constant distance. The slit-shaped light beam reflects from the examined surface at a low grazing angle and reaches the detector. This technique enables high scanning velocities ranging from 2 to 20 cm/s and large line widths exceeding 10 cm. EOL inspection results closely resemble the actual subject and hence can be easily interpreted [95]. An EOL scanner utilizes a slit-illuminated light source to generate a rectangular light band on the surface of the scanned object. The intensity of the light band is constant in the main zone but decreases sharply at the edge due to diffraction effects. The detector of the EOL scanner operates in the middle of this transition zone or the "edge of light" zone, where the intensity gradient is high [94].

The detector maintains a fixed position relative to the light source and measures the reflected light intensity from the surface. The light intensity is uniform for a smooth surface. Any surface irregularity alters the reflection angle of the light, which consequently affects the light intensity at the detector. The scanner moves along the surface of interest and produces a high-resolution map of the surface morphology.

2.8 *Combined NDI techniques for corrosion detection of aircraft structure*

Most of the NDI techniques, as discussed above, were found to be inappropriate to inspect corrosion in bends and hidden areas in the aircraft. Also, these techniques are not fully successful in detecting some special common defects like exfoliation in fasteners, fatigue cracks, etc. In this case, conventional and non-conventional NDI methods can be combined to give an unfailing means for detecting and quantifying defects [96]. As part of Tektrend's research program in NRC, Canada, three NDI techniques were combined to develop a system for corrosion and exfoliation detection in aircraft structures-PANDA Inspection System [96]. The system is modular and portable and configured for UT and ET transducer positioning for acquisition and imaging and guided wave (GW) inspection, EOL, or D-Sight for providing cost-effective, practical non-destructive evaluation [97]. This combined NDI system is found to perform better compared to the individual NDI techniques.

For better understanding, Table 1 shows comparative data for various NDI techniques, focusing on the pros, cons, and performance metrics of each corrosion detection method.

Table 1. Various NDI techniques focusing on the pros, cons, and performance metrics

NDI Technologies	Advantages	Disadvantages	Inspection type	Measurement mode	Inspection area	Cost
Ultrasonic	Fast; Inspection of corrosion or flaws in large areas	Require contact with the surface; surface should be smooth	Contact [5]	Mechanical vibration in the range of 1 to 10 MHz	Thickness measurements and crack detection [98]	Low cost [99]
Eddy current	Quick and moderate cost; no contact required	Limited to conductive materials; low penetration depth	Non-contact (optical) [100]	Alternating currents [100]	surface or near-surface defects [100]	Inexpensive
Radiography	A wide range of materials can be inspected; matured technology	Requires access to both sides of the aircraft structure being inspected; costly; safety hazards	Non-contact	X-rays [98]	Pores and cracks [98]	Relatively inexpensive [101]
Thermography	High sensitivity; best suited for surface corrosion detection; fast	Poor resolution of thick surfaces	Non-contact (optical) [5]	Thermal radiation [101]	Disbonds and delaminations in composite parts [101]	High cost [101]
Microwave	Suited for under-coating corrosion detection; high sensitivity; can inspect surfaces in depth	Complex data analysis	Non-contact [76]	Microwaves used as heat sources in the frequency range of 300 MHz to 300 GHz [76]	near-surface and subsurface damage [76]	Relatively inexpensive [101]
Terahertz	High resolution; can inspect under-coating corrosion; quick	Not matured technology; complex data interpretations	Non-contact	Electromagnetic waves with frequency between 0.1 and 10 THz [85]	Surface defects, hidden voids, delaminations, and bending damage	Expensive [102]

3. Corrosion sensors

NDI techniques are the most commonly used methods for aircraft corrosion inspection. However, these techniques require a substantial quantity of resources in the form of human resources, investment in machinery, and training of workers. A new trend is the development of corrosion sensors that support non-destructive testing and signal the onset of corrosion in aircraft structures. The fast growth in the business and advancements in fabrication approaches and data logging have contributed to making aircraft corrosion sensors a feasible technology that is gaining popularity.

3.1 *Type of corrosion sensors*

A brief description of several types of corrosion sensors for aircraft structures is as below.

3.1.1 *Corrosion coupons*

The corrosion rate in coupons is determined by weight-loss measurements. They are installed to duplicate the corrosion rate experienced in the structure being monitored. Coupons are generally used as witness plates for calibrating other sensors and can be used to estimate the effectiveness of the corrosion protective treatments or evaluate the suitability of a specific material for a particular system [103], [104].

3.1.2 *Linear polarization resistance sensors*

Linear polarization resistance (LPR) corrosion sensor is a valued tool that can be affordably deployed to get both general and localized corrosion measurements instantaneously, i.e., the real-time electrochemical measurement of corrosion. These sensors have gained attention for the CBM approach for monitoring corrosion in aircraft [105].

3.1.3 *Galvanic sensor*

In this type of sensor, the current or voltage which is generated by two separated dissimilar metal electrodes is used to measure the corrosive environment [19]. Galvanic corrosion occurs in alloys or in the joints of dissimilar metals/ conducting materials, due to the potential difference between the metal undergoing corrosion and the other conductors. In the case of aircraft structures, galvanic corrosion is mainly visible when aluminium is in contact with the conducting CFRP plates in a corrosive environment [106]. The corroded metal has a low reversible potential and acts as the anode, while the other conductor acts as the cathode. In this case, aluminium (less noble) acts as the anode, and carbon fibre (more noble) acts as the cathode. Both are connected to each other to form a complete circuit where the ion current in the electrolyte and the electron flowing through the metal conductors complete the current flow. In short, a primary cell is formed with two different metals or alloys covered by the electrolyte. This current or voltage is measured to evaluate the corrosion in that specific area [107], [108].

3.1.4 *Electrochemical impedance spectroscopy*

The electrochemical impedance spectroscopy (EIS) technique can be used to evaluate the degradation of coatings [109], [110]. The EIS electrodes are embedded under the coating and various elements like the coating, substrate, and electrolyte are modelled into the AC circuit as circuit elements. The resistance and capacitance values of each circuit element are determined by measuring the changes in impedance as a function of frequency at a small applied potential. The inferred values indicate the state of the coating [110]. For example, a coating (paint) generally exhibits a capacitive behaviour with very high impedance at low frequency. The low-frequency impedance changes are very sensitive to coating and substrate health. As the coating starts absorbing moisture, the impedance in the low-frequency region starts diminishing and becomes independent of frequency. The decrease in impedance with the rise in moisture absorption occurs well before any visual indications of deterioration and can give early warnings of corrosion. For making real-time measurements in aircraft structures in-situ EIS corrosion sensors are required to make the detection of corrosion easier and practical [110].

3.1.5 *Electrochemical noise*

Electrochemical noise (EN) has great potential for measuring general and localized corrosion rates in aircraft materials. It was studied in the late 1970s and early 1980s for the detection of localized corrosion phenomena like pitting, crevice, and cavitation attacks [111]. This technique is based on the measurement of fluctuations in electrochemical potential and corrosion current that occur during corrosion. These fluctuations which occur on the corroding electrode are called electrochemical noise. The EN, including both the current signals (ECN) and the potential signals (EPN), can be captured using a reference electrode and one or more working electrodes, often supplemented by auxiliary electrodes [26]. The electrodes are embedded in a protective coating to ensure the accuracy of the information collected.

Each type of corrosion, including uniform, pitting, and crevice corrosion, produces a distinct "fingerprint" in the signal noise. This fingerprint can be used to predict the type and severity of the corrosion. This is the main advantage of the EN technique as it can provide good pointers for detecting the mechanism of corrosion. EN has been found to be a promising technique for the detection and monitoring of pitting corrosion which is otherwise difficult to analyse [112]. Furthermore, it can be used to estimate the corrosion rate as well. However, the major factors limiting the potential application of EN in aircraft corrosion detection are its complex analysis process and the absence of a continuous aqueous medium for EN measurements. The success of the technique mainly depends on the signal-capturing ability of the electrodes. For a meaningful EN measurement, an aqueous medium is generally needed. In practical situations, aqueous medium/corrosive solutions can only be seen in very thin and discontinuous layers, which are formed due to the absorption of moisture or water seepage through cracks or condensation. This is a serious reservation when using EN sensors in aircraft structures [26].

3.1.6 *Acoustic emission*

The Acoustic Emission (AE) technique, based on the capture of the acoustic waves generated from the energy released during the damage process, can be used to monitor the propagation of corrosion, stress corrosion cracking, and the evolution of local damage in the structure [113]. When a material experiences a fracture, the strain energy stored within it is released, resulting in the formation of new cracks and the emission of elastic waves. These elastic waves are detected by an Acoustic Emission (AE) sensor on the surface of the metal, which converts the vibrations into an electrical signal. The electrical signal generated by the sensor is a measure of the crack generated [114].

There has been a lot of research on the use of AE for the detection of various types of corrosion in Al alloys [115]. Idrissi et al. [116] studied the use of AE for the detection of pitting corrosion in Al 2024 alloy, which is most used in aircraft. It was reported that pit germination did not produce detectable AE signals, while the gaseous release in the form of micro and macro-bubbles could give rise to detectable AE activity. With the advances in instrumentation, it would be possible to detect the feeble AE signals resulting from corrosion. The major obstacle in the use of AE sensors is the challenges involved in denoising the signal in various corrosion environments [26]. The use of AE sensors to identify the type and location of corrosion in real-life structures like aircraft remains a challenge due to the complex analysis process [117].

3.1.7 *Corrosion-indicating paint*

Corrosion-indicating paints are those paints that respond to chemical changes associated with corrosion by changing colour or fluorescence. Several fluorescent materials, which are either redox or metal ion complexes have been identified as possible corrosion-sensing coatings for aircraft [118]. These corrosion-sensitive materials, if incorporated into paints, can provide an early warning of corrosion. The redox materials which are usually non-fluorescent in the reduced state become fluorescent upon oxidation and indicate corrosion [119]. For example, the metal ion complex-based corrosion indicators react with aluminium oxide on corroded aluminium to give a fluorescence that can be photographed in UV light.

3.1.8 *Optical fibre sensors*

In recent years, optical fibre sensors have been increasingly utilized for structural health monitoring in the aerospace, civil, and marine industries [120]. The main advantages of optical fibre sensors include insensitivity to electromagnetic radiation, spark free, light weight, small size, and minimal intrusiveness. All properties make these sensors suitable for structural health monitoring in aircraft structures. Optical fibre sensors are an effective technology for detecting corrosion in concealed areas, such as under sealant beads and lap joints in aircraft [121]. In a study by Ji et al. [122], optical fibre sensor with fibre Bragg grating (FBG) was used to study the corrosion of an Al-steel lap joint. The change in strain caused by the bulging due to corrosion was calibrated against wavelength shift to identify corrosion. Optical fibre-based corrosion sensor was fabricated by depositing aluminium film after removing the cladding and the changes in the features of light when corrosion proceeds were studied by Benounis and Jaffrezic Renault [123].

When corrosion starts, parts of the metallic coating get removed and the core comes in direct contact with the corrosive/acidic electrolyte. This causes the attenuation of higher guided modes to decrease significantly which can be detected easily through optical measurements. The use of optical fibre sensors in aircraft corrosion detection is still in the developing stage and is mainly limited to laboratory studies till now.

3.1.9 *MEMS-based sensors*

MEMS sensor is a low-cost, non-intrusive approach for finding failures in high-value structures [124]. They can be permanently integrated into the structure of an aircraft and periodically monitored using wireless or wired data collection units. This allows for real-time monitoring of the aircraft's structural integrity, enabling early detection and prevention of potential failures. MEMS sensors can also be easily integrated with control and signal processing. Statistical sampling can be used for predictions of the occurrence of corrosion over large surfaces [125]. This technology coupled with Structural Health Monitoring System (SHMS) will help in quickly determining the health of the ageing aircraft structures. MEMS devices are usually fabricated in silicon and can be used as corrosion sensors, where the changes in the vibration characteristics of micro-cantilever systems with the progress of corrosion can act as the basic detection principle.

3.1.10 *Carbon-based sensors*

Functionalized graphene, because of its high selective sensitivity to certain molecules, environmental factors, etc. can be used for corrosion sensing in aircraft [7]. For example, graphene oxide (GO) has found application in various types of sensors like capacitive sensors, surface acoustic waves, and Radio-Frequency Identification (RFID) sensors because of its sensitivity to moisture [126], [127]. It can also be used as a temperature sensor exhibiting excellent sensitivity, repeatability, and environmental stability [128]. Researchers have used graphene and other carbon derivatives to fabricate thin-film chemical sensors, especially ion-selective field-effect transistors (ISFETs), which are potentiometric sensors that can be used for corrosion monitoring, environmental monitoring, etc.

3.2 *Real-time corrosion sensor systems*

As discussed already, several sensors can be combined in a single unit to measure various parameters in the corrosion matrix and correlate them to the corrosion rates. A few such systems that have gained popularity in recent times are discussed below.

3.2.1 *Analatom corrosion sensor system for aircraft*

Analatom Incop., USA has developed a micro-linear polarization resistance (µLPR)-based corrosion sensor for corrosion monitoring in aircraft especially in corrosion-prone areas [9]. Analatom's µLPR corrosion sensor can provide direct real-time measurements of electrochemical corrosion activity in the monitored part for SHM applications by providing an identical corrosion rate of the metal on which they are placed. The sensors are constructed from the same temper and alloy as the structure being monitored. The µLPR sensors are interdigitated electrode types with a spacing of 150-300 µm between the electrodes. They are ultrathin and flexible and can be placed on bare metal surfaces and beneath the coatings. The µLPR sensor is fabricated from metal shim stock of the source material and bonded to a Kapton tape as shown in Figure 6.

Photolithographic techniques and Electro-Chemical Etching (ECM) are used for the fabrication of the sensors from the shim stock. For the data acquisition from µLPR sensors, a data acquisition unit namely, Analatom's AN110 is attached to the sensor network. The AN110 DAQ unit is connected to eight µLPR sensors along with time of wetness (TOW) sensors and a humidity/temperature sensor. Various parameters, such as linear polarization resistance (LPR), resistance for TOW, temperature, and humidity, are measured and stored in the data acquisition unit. The data from the unit can be retrieved using either a wired interface, such as RS232 or RS485, or wirelessly using the ZigBee protocol.

The data is further analysed to keep track of corrosion in the areas. Micro-linear polarization resistance corrosion sensors along with AN110 provide a complete real-time monitoring of corrosion for structural health monitoring applications [129].

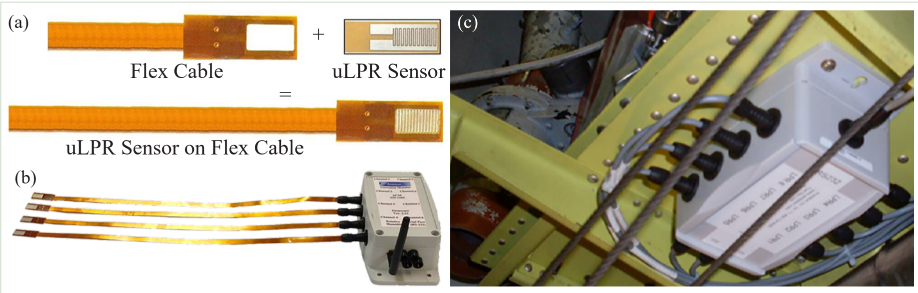

Figure 6. (a) Assembly of two-electrode LPR onto a flex cable (b) AN110 connected to four uLPR flex sensors and (c) Embedded SHM system installed in the rear fuel bay of aircraft [9]

3.2.2 *Luna sensor suite for aircraft corrosion monitoring*

Another common corrosion monitoring sensor system is the Luna Sensor Suite for Aircraft Corrosion Monitoring (LS2A) which is being used for evaluating the effectiveness of corrosion control practices and tracking corrosion of individual aircraft [10]. The LS2A system has proven to be a valuable tool in identifying the underlying factors that contribute to airframe corrosion.

By continuously recording environmental conditions and atmospheric corrosivity, the system can measure specific parameters such as relative humidity, surface temperature, air temperature, contaminants, and aluminium corrosion rate. This information is then used to enable condition-based maintenance (CBM) for corrosion, allowing for more effective and efficient maintenance practices.

With this real-time measurement of these parameters, it is possible to track the severity of conditions that cause corrosion. It can help in reducing the maintenance checks and the cost. The LS2A monitoring system is capable of detecting the onset of corrosion damage to aircraft parts, even before visible changes are observed. This early detection can help reduce maintenance costs and increase aircraft availability. While the system was designed specifically for aerospace applications, where corrosion can significantly increase maintenance costs and labour, the LS2A platform can also be used to monitor and survey corrosion severity in a variety of other settings. These include industrial facilities, ground equipment, storage, and distributed assets such as power transmission or pipelines and ground vehicles.

Several sensor nodes are distributed at various corrosion hotspots in the aircraft and the data from them is collected and analysed. The LS2A monitoring system provides a comprehensive view of the overall structural health of an aircraft, including an assessment of its structural integrity. By tracking and anticipating the corrosive effects on the entire aircraft, the system allows maintainers to develop effective mitigation strategies. The sensor system is capable of measuring, processing, and storing both instantaneous corrosion rates and long-term cumulative corrosion data. This provides maintainers with real-time corrosion information as well as an ongoing record of the corrosion history of a particular structure. By analysing this data, maintainers can pinpoint short-term events that correspond with particularly high corrosion rates and develop strategies to address them.

4. Corrosion detection using artificial intelligence techniques

In recent times, Artificial Intelligence (AI) and Machine Learning (ML) techniques have significantly contributed to corrosion detection by simplifying processes, reducing labor, saving money, and improving overall efficiency in various ways like automation of detection, early detection, real-time monitoring, predictive maintenance, effectiveness of data analysis, cost reduction, optimization of resource allocation, improved accuracy, reduced frequency of checks, security improvements, and continuous learning [37].

Aviation experts like Boeing and Airbus have turned to cutting-edge technologies of AI/ML for corrosion detection and maintenance in recent times. Boeing has been actively investing in AI and ML for corrosion detection. Boeing utilizes computer vision algorithms and ML techniques to analyze high-resolution images of aircraft surfaces. These images are captured during routine inspections using drones and other imaging devices [130]. Airbus, another major aircraft manufacturer, has implemented AI and ML in its predictive maintenance programs, including corrosion detection. Airbus collected data from various sensors, such as ultrasonic thickness gauges and corrosion potential sensors, installed on their aircraft. They used ML algorithms to analyze this data along with historical maintenance records [131]. Pratt & Whitney, a manufacturer of aircraft engines, incorporated AI and ML into their corrosion monitoring systems to ensure engine component integrity. United Airlines, one of the major U.S. carriers, adopted AI and ML to improve the inspection process for their aircraft fleet. United Airlines deployed AI-driven robotic inspection systems equipped with cameras and sensors to assess the condition of aircraft surfaces. ML algorithms were used to analyze the collected data and identify corrosion or damage [132].

Apart from the industrial adoption of AI/ML for corrosion detection in aircraft, there has been a lot of research carried out on the same recently. Nour Nayef introduced a novel methodology for identifying defects in the exteriors of aircraft using image processing and machine learning [133]. Cha et al. [134] used a deep learning-based approach for detecting cracks in aircraft structures utilizing Convolutional Neural Networks (CNNs). They utilized a dataset containing images of both cracked and uncracked specimens for training and evaluation. Miranda et al. [135] proposed a method for automated detection and classification of defects in aerospace composite structures through deep learning with an accuracy of 97.5%. They employed a high-resolution image dataset featuring various defect types in composite structures for training and evaluation. Meng et al. [136] introduced a deep learning-based method combining CNNs and Recurrent Neural Networks (RNNs) for crack detection in aircraft structures. Furthermore, similar research conducted by Shafi et al. [137] centers on developing a real-time defect detection system based on deep learning to enhance aircraft manufacturing and control performance. The authors propose an AI-driven defect detection system capable of identifying defects prior to the integration stage, thereby minimizing rework delays and optimizing production time and costs. In a research paper by Balakrishnan et al. [130], they focus on creating a novel approach for inspecting aircraft surfaces to detect defects stemming from corrosion, cracks, and stains.

While the use of AI and machine learning techniques for corrosion detection offers numerous advantages, it also presents several limitations. The primary limitation is the quality and availability of data. Effectively training AI models requires substantial volumes of high-quality, labeled data. If historical data on corrosion are limited or not adequately recorded or representative, the performance of AI techniques may be significantly impacted. Secondly, corrosion occurs in an uncountable variety of forms and locations; hence, it is tough to generalize AI across a wide range of situations. At times, this complexity may result in some missed detections or false positives. Moreover, in critical applications like aircraft, the complexity of machine learning algorithms makes them extremely difficult to interpret. Furthermore, AI systems may be susceptible to cyber-attacks that could compromise the integrity of corrosion detection processes. Some more challenges also relate to the setup cost and the requirement for specialist expertise. The introduction of AI techniques with existing detection technologies and workflows can also be cumbersome and will need significant modifications.

Hence, proactively addressing the challenges for AI in corrosion detection is required to bring out the benefits while at the same time mitigating the risks. This can be achieved through robust data collection and augmentation to ensure diversified training datasets, model interpretability, and evaluation processes to reduce false positives and negatives, and phased implementations to manage costs. Above all, ensuring human oversight and transparency through AI technologies fosters trust, leading to safer and more effective corrosion management.

5. Outlook and challenges

It is essential that the maintenance and the replacement costs be minimised for the aircraft. Each of the detection techniques, whether it be, NDI methods or sensors have its own advantages and disadvantages. Hence, the selection and use of the right detection technique depending on the physical conditions of the aircraft is of utmost importance.

5.1 *Challenges in offline corrosion detection systems*

One of the major challenges with the conventional and commercial NDI techniques is that they are mainly focused on visual and field detection methods which require the grounding of the aircraft for several days. Also, these techniques are time or usage (flying hours) based rather than condition based. They are also less effective in cases where corroded areas are not easily accessible. Additionally, traditional visual inspections are conducted by human operators who scan the aircraft fuselage looking for corrosion, cracks, and incidental damage. However, this is a costly and time-consuming procedure apt to be subjected to human mistakes caused by mental fatigue and boredom. Furthermore, there are limitations associated with each of the NDI techniques. For instance, eddy current techniques are limited to conductive surfaces and have low penetration depths, thus making it difficult to detect corrosion underneath. Similarly, terahertz and microwave techniques require complex data interpretations, while few of the other NDI techniques are highly expensive and sophisticated. Another crucial factor in corrosion detection and monitoring is the frequency of maintenance checks. Although certain guidelines are being followed for this, they are not completely foolproof, as one cannot accurately predict where and when corrosion occurs. Most of the NDI techniques are schedule-based; they lack the ability to monitor the real-time conditions of the aircraft structure, which is crucial in timely corrosion detection. Active sensors (real-time sensors) can provide an insight into the real-time physical conditions of the aircraft which is useful in deciding the maintenance schedules. But the use of real-time sensors for monitoring the aircraft structure is not a trivial task. It requires careful planning and optimization of the sensor placement, as well as robust and reliable methods for data analysis and damage identification.

5.2 *Challenges in real-time corrosion sensors*

One of the challenges is to determine the optimal number and location of sensors that can capture the most relevant information about structural behaviour and health. This can depend on various factors, such as the geometry, material, loading conditions, and damage scenarios of the structure. Some researchers have proposed different methods for sensor placement optimization, such as using Fisher information matrix (FIM), particle swarm optimization (PSO), genetic algorithms (GA), or other criteria [138]-[140]. Another challenge is to develop efficient and accurate algorithms for identifying the location and severity of damage based on the sensor data. This can be formulated as an inverse problem, where the unknown parameters are estimated from the measured responses. Some techniques for solving this problem include using modal data, frequency domain analysis, time domain analysis, optimization methods, machine learning methods, etc. [141], [142]. Yet another problem is placing the sensors in the existing aircraft structures as it involves a lot of technical and practical difficulties. These sensors have to be compatible with the existing aircraft systems, such as power supply, communication, and data processing. They also have to be reliable, accurate, robust, and lightweight. Moreover, the installation and operation of real-time sensors can incur additional costs and maintenance requirements for the aircraft. The sensors have to be calibrated, tested, and replaced periodically to ensure their functionality and accuracy. The sensor data have to be stored, transmitted, and secured properly to avoid data loss or tampering. Furthermore, the sensor system also has to comply with the safety and regulatory standards of the aviation industry.

These challenges are still active areas of research and development, and there is no single best solution for all cases. However, the potential benefits of using real-time sensors for aircraft structure monitoring are significant, such as improving safety, reliability, performance, and maintenance of the aircraft.

5.3 *Digital twin technology for corrosion monitoring*

The concept of digital twin, primarily a virtual replica of any conceivable physical entity, is a highly transformative technology with profound implications [143]. It has been adopted by various industries for product development, design optimization, performance improvement, and predictive maintenance.

This concept of digital twin originated in the aerospace industry and ever since the aerospace industry has been a keen adopter of digital twins, using them to gain real-time insights into their assets and operations [144], [145]. Figure 7 explains the digital twin and its related technologies. A digital twin of an aircraft is a virtual replica of a real aircraft that can simulate its behaviour, performance, and health based on sensor data and models. A digital twin can help aerospace companies to monitor, analyse, and optimize the aircraft operation and maintenance in real time. It can also help to detect and predict potential faults, failures, or damages in the aircraft structure or systems, and provide recommendations for corrective actions. Digital twins are becoming more and more popular in the aerospace industry, as they can provide significant benefits such as improving the safety, reliability, efficiency, and profitability of the aircraft.

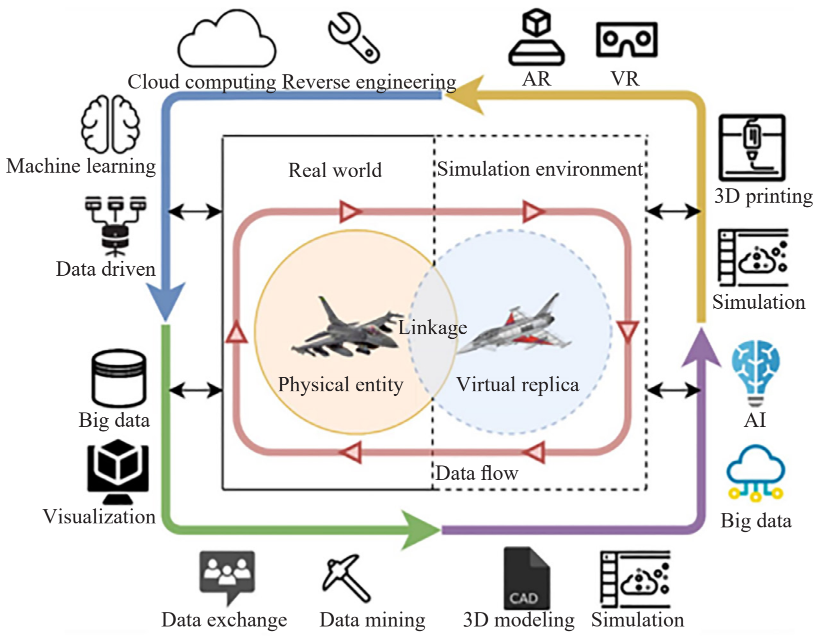

Figure 7. Digital twin and related technologies [122]

In recent times, the concept of digital twin has also gained attention in the structural health monitoring (SHM) for aircraft [146]-[149]. The development of a digital twin which provides a complete model of the physical conditions of an in-service aircraft could be one of the most innovative approaches to optimise the maintenance and replacement schedules of aircraft. This can be a path breaker in timely corrosion detection as it can be used to detect and monitor corrosion following a more efficient and cost-effective corrosion management strategy. This can minimise maintenance costs and downtime, and avoid unexpected failures associated with corrosion. The major challenges and limitations that need to be addressed in this model creation are the collection of accurate data about the physical condition of the aircraft, data quality, security, integration, validation, verification, etc.

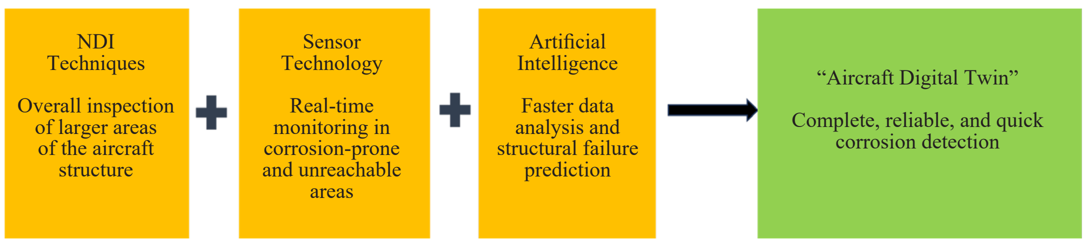

Figure 8. The aircraft digital twin model for complete and quick corrosion detection

In this regard, we propose combining three different techniques, namely the NDI methods, real-time sensors, and AI-related techniques, each of which compensates for the drawbacks of the other, allowing the development of a complete digital twin of an aircraft structure as depicted in Figure 8. The different advanced NDI techniques provide rapid and accurate scanning of aircraft structures to provide information about the physical conditions. The sensors installed in different regions especially those inaccessible to the NDI techniques, can provide real-time information about corrosion taking place in such regions. The AI and ML techniques which are at their peak now, can be used for faster analysis of the data collected and prediction of the lifetime of the structure. The proposed aircraft digital twin model can provide a complete solution to corrosion detection in aircraft.

Creating a digital twin of an aircraft's physical conditions is a complex and challenging task. Developing a digital twin of an aircraft requires a deep understanding of its physical properties and the ability to accurately model its behaviour. Developing digital twins for corrosion detection in the aircraft industry presents a unique set of practical challenges due to the stringent safety regulations, complex materials, and dynamic operating environments involved. Here's an in-depth look at these major challenges:

5.3.1 *Selection of the right detection techniques*

One of the major challenges will be to choose the right NDI techniques and sensor technologies depending upon the characteristics of the aircraft like size, metal/composite materials used, age, flight conditions, etc., of the aircraft.

5.3.2 *Data Integration*

Aircraft are equipped with numerous sensors that monitor structural integrity, environmental conditions, and operational parameters. Integrating data from these sensors, which can include acoustic emission, temperature, humidity, and pressure readings, requires advanced data management solutions. Failures and errors in sensors can lead to a catastrophe. The initial challenge is corruption and data loss stemming from the faulty functioning of sensors, wiring, and receivers [150]. Such data loss or corruption can lead to incorrect assessments of an aircraft's operational condition, resulting in misguided protective actions. To mitigate data loss, various techniques have been suggested in the literature, including K-nearest neighbors [151], Delaunay triangulation [152], multichannel singular spectrum analysis [153], and compressive sensing [154]. By implementing these methods, it is possible to estimate the values of lost or corrupted data, thereby reducing the risk. Calibration of the sensor is also of acute importance to have error-free data with the highest accuracy.

The next challenge is the digitalization of aircraft control, design, management, maintenance, overhaul, etc. through DTs, which extract useful information from received data. The primary challenge here is managing the vast amounts of data called big data, which is typically defined by the 4 Vs: Volume, Velocity, Variety, and Veracity. Volume pertains to the continuous and relentless generation of data, while Velocity highlights the rapid pace at which this data is produced, particularly in digital twin (DT) applications. Variety relates to the diverse sources and types of data generated, such as voltage signals and health conditions. Lastly, Veracity addresses the quality of the data received by the digital twin [155].

To address big data errors, researches have adopted several techniques. Tavares et al. [156] assessed the effectiveness of machine learning in tackling the computational challenges associated with adaptive digital twins (ADT), focusing specifically on model updating and overall efficiency. Heim et al. [157] utilized probability density functions to address the challenge of limited run-to-failure data. Meanwhile, Gocket et al. [158] employed a nearest neighbor algorithm along with Gaussian Process regression to perform load mapping and stress estimation based on Computational Fluid Dynamics (CFD) simulations. Wang et al. [159] utilized statistical learning techniques to address the high computational costs associated with predicting the remaining useful life of a damaged aircraft structure based on a probabilistic distribution.

The importance of data security increases significantly when digital twins (DTs) are utilized for monitoring the condition of aircraft. Data security is essential for safeguarding databases against cyberattacks, including ransomware, which is a type of malware designed to compromise data, as well as data theft and cyber attacks [160], [161]. Another challenge is the inconsistent data formats as data from various sources may come in different formats, making it difficult to create a unified model. Standardizing data formats for seamless integration is a critical but complex task. Also, the sensor data that feed the digital twin have to be accurate, reliable, complete, and consistent. Any missing, noisy, or corrupted data can affect the quality and validity of the digital twin simulation and analysis. Moreover, the sensor data have to be protected from unauthorized access, modification, or deletion.

The digital twin model has to provide a user-friendly interface for the human operators and users, such as pilots, engineers, technicians, etc. The interface has to display the relevant information and insights from the digital twin in an intuitive and understandable way. The interface also has to allow the human operators and users to interact with the digital twin, such as providing inputs, feedback, commands, etc. The human-machine interaction has to be effective and efficient.

5.3.3 *Real-time updates*

Achieving optimal performance in DTs requires sophisticated strategies to ensure that QoS (Quality of Service) requirements are met, enabling seamless real-time processing and analysis of IoT (Internet of Things) data. IoT in aircraft refers to the integration of interconnected devices and sensors within aviation systems to collect, transmit, and analyze data in real time.

The technical challenges of ensuring QoS for real-time decision-making and IoT data processing in digital twins DT are heightened by the fact that DT typically operates on virtualized computing, storage, and networking resources. This reliance on virtualization stems from its well-known benefits in scalability and cost-effectiveness.

Sojka et al. [162] introduced a middleware based on Common Object Request Broker Architecture (CORBA) that offers a consistent Application Programming Interface (API) for distributed soft real-time applications. This middleware allows for the reservation of diverse resources with real-time scheduling capabilities within a distributed environment. Serverless computing and function-as-a-service (FaaS) platforms have been proposed to achieve better QoS [163], [164]. Besides, Sensor Reliability and Calibration also plays a crucial role. Aircraft operate in demanding conditions, and sensors must provide precise and accurate readings.

As highlighted by Sadeghi et al. [160], existing technologies like piezoelectric and optical fiber sensors have limitations that raise concerns about data integrity and reliability. Therefore, it's essential to adopt a more practical approach to integrate Emerging Operational Conditions (EOCs) for accurate structural life prediction.

Two AI-based methods were developed by Lai et al. [148], one utilizing a single fidelity surrogate model and the other employing a deep learning algorithm to compute and identify loads from strain gauge data. These methods were tested on a model aircraft wing to demonstrate the concept of individualized load inputs for the structural prognostics model in the Aircraft Digital Twin (ADT). However, implementing this approach necessitates the installation of load sensors across the entire wingspan, which may not be feasible in a real aircraft due to weight and design constraints.

Computational challenges in managing digital twins include the need for substantial processing power and minimized latency. Real-time analysis of data from multiple sensors requires significant computational resources to ensure the digital twin can quickly process and analyze information, delivering timely insights that are crucial for flight safety. Additionally, reducing latency in data transmission and processing is essential; any delays can hinder the ability to respond rapidly to emerging corrosion issues, which is especially critical in aircraft maintenance.

5.3.4 *Validation against physical models*

Modeling is the core of digital twins (DTs) in aircraft systems, capturing the precise characteristics of an aircraft or its components in a virtual environment. Three primary modeling methods are employed: White Box Model (WBM), Grey Box Model (GBM), and Black Box Model (BBM). WBMs, are the conventional models that characterize the behavior of aircraft, engines, wings, and other components using well-established techniques such as Equivalent Electrical and Thermal Circuit (EETC), Finite Volume Method (FVM), Finite Element Method (FEM), and Finite Difference Method (FDM). WBMs are generally accurate and reliable, however their computational speed tends to be slower compared to other modeling types. The advancements in distributed and edge computing improve their processing speed [165]. BBM are typically ultra-fast, adaptive, and capable of retraining for new scenarios, but their primary drawback is their heavy reliance on data quality. Any corruption or insufficiency in data can lead to inaccuracies and erroneous decisions [166]. To address the limitations of both WBMs and BBMs, GBMs leverage aspects of both approaches to correlate inputs and outputs. By integrating physical logic with data science, GBMs effectively model the behavior of components that may not be fully understood. This makes them particularly suitable for use in digital twins, offering high accuracy, adaptability, rapid estimation, and reliable results [160].

The model should be able to capture the essential features and dynamics of the aircraft, as well as account for the uncertainties and variabilities in the operating conditions. Also, the digital twin has to be integrated with the existing aircraft systems, such as power supply, communication, data processing, control, etc. The integration has to be seamless and compatible, without causing any interference or disruption to the normal operation of the aircraft.

5.3.5 *Cost and resource allocation*

The upfront costs associated with developing and deploying a digital twin system that involves sensors, software development, and integration. Airframe maintenance is a primary cost driver in the aircraft Maintenance, Repair, and Overhaul (MRO) sector. As aircraft age and accumulate more flight hours, maintenance costs are expected to increase significantly. This rise is largely due to time-dependent failure mechanisms, such as fatigue and corrosion, which become more prominent over time. Along with this regular updates and maintenance of the digital twin infrastructure require ongoing investment in technology and skilled personnel, which can strain budgets. The high-fidelity models can also be computationally expensive and complex to implement and maintain.

These are some of the main challenges for creating a digital twin for an aircraft for corrosion monitoring. However, these challenges are also opportunities for further research and development in this field. The potential benefits of using a digital twin for an aircraft are significant, such as improving safety, reliability, efficiency, and profitability of the aircraft. Therefore, it is an important and active area of research and development in the aerospace engineering field.

6. Conclusion

Given the significance of air transportation in contemporary society, it is crucial to ensure the dependability of aircraft structures. Despite the growing utilization of composite materials, certain components of aerospace structures are still constructed from metals, which cannot be entirely eliminated. There is no single, straightforward method for combating corrosion. This review is organized to provide valuable insights for researchers.

The most important highlights of this review paper could be shortlisted as follows:

The review presents various techniques for corrosion detection and monitoring in aircraft structures, including non-destructive inspection (NDI) methods. Each detection technique is discussed, highlighting its advantages and disadvantages, which makes it challenging to detect all types of corrosion using a single method.

Real-time sensors can be embedded in critical aircraft components to provide continuous and targeted monitoring of aircraft health. These sensors provide instant feedback, enabling proactive maintenance and reducing the risk of unexpected failures.

It explores the application of artificial intelligence (AI) and machine learning (ML) techniques for corrosion detection and rapid analysis. By leveraging data-driven approaches, AI and ML can enhance the accuracy of corrosion assessments and facilitate quicker decision-making, potentially improving maintenance strategies and extending the lifespan of aircraft structures.

We also introduce a novel approach that combines various methods to create a digital twin, aimed at accurately simulating the behavior of physical entities. This integrated solution gives deeper insights in corrosion detection and offers a dynamic tool for optimizing operational efficiency and decision-making.

The digital twin (DT) concept is an emerging technology that creates a real-time virtual replica of physical entities to characterize their behaviors. This integration aims to improve the accuracy of corrosion detection and predict the remaining useful life (prognostics) of aircraft structures impacted by corrosion and fatigue.

Digital twins are more than just digital shadows; they can interact with the real world through bidirectional data flows. This enables them to not only refine data-driven models using IoT data in real time but also to provide actuation feedback, potentially intervening in the physical environment.

Bringing together expertise from various sectors-such as aerospace manufacturers, software developers, data analysts, and research institutions-collaborative efforts can drive innovation and accelerate the implementation of AI and ML technologies. Additionally, collaboration fosters the development of AI algorithms tailored to specific challenges in corrosion detection and structural health monitoring, ultimately enhancing safety, efficiency, and maintenance strategies in the aviation industry.

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Conflicts of interest

The authors declare no conflict of interest.

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