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# Multi-Sensor Data Fusion for Early Warning of Corrosion-Prone Conditions in Closed Zones of a Medical Rescue Aircraft

**Patryk Ciężak [1,*], Michał Dziendzikowski [2], Artur Kurnyta [2], Lourdes Vázquez-Gómez [3], Luca Mattarozzi [3], Alessandro Benedetti [4], Adrianna Nidzgorska [2] and Andrzej Leski [1]**

[1] Faculty of Mechatronics, Military University of Technology, 2 gen. Sylwestra Kaliskiego Street, 00-908 Warsaw, Poland
[2] Air Force Institute of Technology, 6 Księcia Bolesława Street, 01-494 Warsaw, Poland
[3] National Research Council – Institute of Condensed Matter Chemistry and Technologies for Energy, Corso Stati Uniti 4, 35127 Padova, Italy
[4] National Research Council – Institute of Condensed Matter Chemistry and Technologies for Energy, Via de Marini 6, 16149 Genova, Italy
* Correspondence: patryk.ciezak@itwl.pl; Tel.: +48-782580303

## Featured Application

The proposed multi-sensor monitoring architecture is intended for hidden and difficult-to-access structural zones, where early warning of corrosion-prone conditions can support targeted inspection, local drying or cleaning, and condition-based maintenance. Within the proposed hierarchy, persistent warning states trigger follow-up diagnostics: PZT sensing localizes suspect subregions, while eddy-current sensing verifies and monitors local damage growth. Although demonstrated on a medical rescue helicopter, the methodology is transferable to civil engineering structures with similarly inaccessible moisture-retaining zones.

## Abstract

Early identification of corrosion-prone conditions remains a major maintenance challenge in closed, hard-to-access structural zones. This paper presents a multi-sensor data fusion approach for early warning of corrosion-prone conditions in selected closed zones of a medical rescue aircraft, as part of a structural health monitoring framework. The study combines sensor selection, installation in restricted-access compartments, and analysis of in-service data collected during helicopter operation. The workflow includes data acquisition, preprocessing, feature extraction, fused interpretation of multi-channel data, and assignment of warning levels linked to maintenance actions. Environmental, conductance, and electrochemical channels provide a first-stage early-warning layer that indicates persistent conditions favorable to long-term corrosion development, rather than direct proof of existing damage. Persistent warning states are intended to trigger staged follow-up diagnostics: PZT sensing localizes suspect subregions, while eddy-current sensing verifies and monitors the growth of local metallic degradation. Field inspection evidence of corrosion in hidden zones supports the practical relevance of this approach. Although demonstrated on an aircraft, the methodology is transferable to other closed or poorly accessible structural zones, including civil engineering applications.

**Keywords:** multi-sensor data fusion; structural health monitoring; corrosion-prone conditions; early warning; condition-based maintenance; medical rescue aircraft; PZT sensing; eddy-current testing; hidden structural zones; civil engineering applications

## 1. Introduction

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Corrosion remains one of the most persistent and operationally significant degradation mechanisms affecting aircraft structures throughout their service life [1]. In aviation, its importance extends beyond material loss, as corrosion may impair structural integrity, accelerate secondary damage, increase inspection burden, and reduce the availability of the aircraft fleet [1,2]. Within a damage-tolerance framework, aircraft structures are allowed to operate with defects only within defined safety limits; therefore, maintaining awareness of damage initiation and progression between scheduled inspections is essential [2]. From this perspective, the earlier unfavorable corrosion-related conditions are identified, the greater the opportunity to prevent progression from a local physicochemical process to a structurally significant defect requiring extensive maintenance [2,3].

A particularly challenging issue concerns closed, difficult-to-access aircraft zones, such as underfloor spaces and enclosed structural compartments, where direct access for routine inspection is limited [3]. These locations may promote the accumulation of moisture, condensation, salts, and operational contaminants, creating local microclimates that differ substantially from the surrounding ambient environment [3,4]. As a result, early-stage corrosion may remain undetected for prolonged periods and become evident only after substantial progression. This problem is further exacerbated by current trends in aerospace materials and protective technologies, including chromate-free coating systems and hybrid structural configurations, which may alter corrosion behavior and complicate the interpretation of degradation processes in service [3,5].

Structural Health Monitoring (SHM) offers a promising framework for observing structural condition during operation; however, traditional SHM approaches in aerospace applications have mainly focused on loads, fatigue, crack propagation, and damage detection, with limited direct consideration of corrosion-promoting conditions [4]. For this reason, Corrosion Health Monitoring (CHM) may be regarded as an important extension of SHM, intended not only to detect the effects of corrosion but also to monitor the environmental and electrochemical precursors associated with corrosion initiation and development [4,5]. In this context, parameters such as temperature, relative humidity, condensation or surface wetness, and free or galvanic corrosion currents are particularly relevant, because together they can provide a more complete representation of the local corrosion environment than any single sensing channel considered separately [5,6].

Recent engineering studies and implementation-focused demonstrations have shown that compact autonomous sensors can be deployed on operational aircraft to collect in-service data on corrosion-prone conditions in selected structural zones [5,6,19,20]. These efforts indicate that the sensing problem is inherently multidimensional: it involves not only selecting suitable sensors but also identifying representative installation locations, accommodating structural and operational constraints, and interpreting heterogeneous data streams recorded during aircraft operation [5,6,19,20]. Moreover, previous observations suggest that corrosion-related phenomena may vary significantly across compartments and sensor locations, underscoring the need for multi-point, multi-parameter monitoring in hidden aircraft zones [3,6,19,20].

From the perspective of advanced sensing and intelligent modeling, the key challenge is not merely measuring individual variables but transforming raw multi-channel observations into an interpretable assessment of corrosion-prone structural conditions [6,7,19,20]. Single-parameter thresholding may be insufficient in structurally constrained aircraft zones, where adverse conditions can arise from the combined effects of multiple environmental and operational factors. Consequently, there is a strong rationale for applying multi-sensor data fusion, signal preprocessing, feature extraction, and AI-assisted decision-support methods that integrate information from multiple measurement channels into a unified, warning-oriented framework [7,11-18,22]. Such an approach aligns with the contemporary evolution of SHM toward more intelligent, data-driven, and decision-supportive monitoring systems that can enhance inspection planning and maintenance targeting in areas where direct inspection remains restricted [4,7,8,15,16,22].

In this context, the present study proposes a multi-sensor data fusion approach for the early warning of corrosion-prone conditions in selected closed zones of a medical rescue aircraft within an SHM framework. The study addresses three main aspects: selecting sensors to monitor

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environmental and corrosion-related parameters associated with corrosion risk, installing the sensor suite in restricted-access and underfloor structural zones, and processing in-service measurement data acquired during aircraft operation [6,7,19,20]. The contribution of the paper is threefold. First, it proposes a practical early-warning framework for corrosion-prone conditions in closed helicopter zones based on in-service environmental, conductance, and electrochemical monitoring. Second, it formulates warning thresholds and persistence-based alert logic intended as transferable screening criteria for identifying conditions favorable to long-term corrosion development rather than as direct indicators of already existing structural damage. Third, it embeds these warning outputs into a staged maintenance-support concept in which persistent alarms trigger follow-up diagnostics: PZT sensing is intended to localize subregions where corrosion-related structural degradation may already be present, while eddy-current sensing is intended to verify and monitor the growth of local metallic damage. In this way, the proposed architecture links early warning, localization, and follow-up monitoring within a condition-based maintenance framework [7,8,11-18,20,22]. Although the validation case considered here is an aircraft structure, the proposed sensing hierarchy and interpretive logic are intentionally formulated at a level that is transferable to other SHM applications, including civil engineering structures with closed, moisture-retaining, or difficult-to-inspect zones.

## 2. Materials and Methods

A methodology was developed to provide early warning of corrosion-prone conditions in selected closed zones of a medical rescue helicopter. The approach comprised six interrelated stages: identification of the most critical closed structural zones, selection of an integrated set of environmental, electrochemical, and SHM/NDT sensors, development of an installation strategy for underfloor and other restricted-access compartments, acquisition of in-service data, signal preprocessing and feature extraction, and multi-source data fusion to derive a corrosion-prone condition indicator and a warning level. The framework was formulated in accordance with the logic of condition-based maintenance, in which inspection and maintenance decisions are triggered by measured condition parameters rather than by fixed time intervals alone [1,2,20,22].

### *2.1. Closed-Zone Corrosion Risk in Medical Rescue Aircraft*

In the present study, the most critical corrosion-prone zone was identified as the underfloor space of the medical cabin. This finding is supported by the aircraft corrosion literature, which consistently identifies hidden, poorly ventilated, and difficult-to-access compartments as particularly vulnerable to undetected moisture accumulation, contaminant retention, and hidden corrosion progression. Underfloor regions are especially important because they combine limited inspectability with a strong potential for long-term electrolyte retention, thereby favoring localized and crevice-type corrosion processes [1,2].

For a medical rescue helicopter, the underfloor cavity is exposed not only to water ingress and condensation but also to mission-specific liquids that can penetrate through floor discontinuities, including panel joints, riveted connections, assembly gaps, cable and pipe penetrations, and locally degraded seals. In operational practice, these liquids may include blood, saline, infusion fluids, glucose solutions, drug solutions, disinfectants, and residues from cabin cleaning and decontamination. Once trapped beneath the floor, such fluids may persist much longer than on exposed cabin surfaces, creating a local environment with elevated humidity, surface contamination, increased electrolyte conductivity, and prolonged time-of-wetness. These are precisely the factors identified in aircraft corrosion research as key drivers of corrosion initiation and propagation [1,2].

From a maintenance perspective, this zone is particularly problematic because direct inspection requires removing floor panels, a labor-intensive, time-consuming, and operationally disruptive process. In practice, such an inspection typically requires the helicopter to be withdrawn from service, transferred to a hangar, and temporarily unavailable for operations. For this reason, the underfloor space is especially well-suited to indirect, continuous monitoring methods that can indicate whether inspection is necessary, when it should be performed, or whether floor removal can be safely deferred within a condition-based maintenance strategy [1].

### 2.2. Sensor Suite Selection

The sensor selection strategy was based on the assumption that reliable corrosion assessment in aircraft structures cannot rely solely on observing already developed damage. Instead, it should combine information on environmental severity, electrolyte presence and surface contamination, electrochemical corrosion activity, and, in a complementary layer, structural consequences detectable by SHM/NDT methods. Recent reviews emphasize that effective aircraft corrosion monitoring requires the integration of physical, environmental, and chemical/electrochemical information, because no single sensing category is sufficient to comprehensively characterize corrosion risk in hidden and complex service environments [2].

Based on the sources reviewed here, the most deployment-ready option for onboard corrosion monitoring is an aircraft-qualified integrated sensor suite developed by Luna, comprising an air-temperature and relative-humidity sensor, a surface-temperature sensor, a surface-conductance sensor, a free-corrosion sensor, and a galvanic-corrosion sensor. This conclusion is based on the combination of functional coverage and formal implementation maturity: the manufacturer explicitly states that the system is qualified for flight safety, operates independently of the aircraft's electrical power system, and continuously records both environmental and corrosion-related parameters over extended periods [6,7,19,20].

The environmental layer comprised the air-temperature and relative-humidity sensor and the surface-temperature sensor. These sensors were intended to characterize the local microclimate within the closed structural zone and to identify conditions conducive to condensation and prolonged wetness. The manufacturer's documentation indicates that both ambient air temperature/relative humidity and local structural surface temperature are continuously recorded. At the same time, TM0416-2016 highlights the importance of such environmental descriptors as contextual information for interpreting corrosion-related measurements [3,6,7,19,20].

The surface conductance sensor represented the contamination/electrolyte layer. According to TM0416-2016, conductance measurements are intended to assess thin electrolyte films and surface contaminants under atmospheric exposure conditions. In the reviewed aircraft-qualified configuration, this function is implemented using noble-metal interdigitated electrodes that continuously measure the electrical conductance of moisture and contaminants, including chloride-bearing deposits. For hidden underfloor zones, this measurement is essential because high relative humidity alone does not necessarily imply a corrosive state. In contrast, elevated surface conductance indicates that a conductive electrolyte layer has actually formed on the monitored surface [3,6,7].

The electrochemical layer consisted of a free-corrosion sensor and a galvanic-corrosion sensor. TM0416-2016 defines the free corrosion sensor as a same-alloy two-electrode sensor operated using electrochemical impedance-based methods to estimate corrosion activity. In contrast, the galvanic corrosion sensor is based on dissimilar materials and on current measurements obtained using a zero-resistance ammeter or precision-resistor techniques. In practical terms, the first sensor provides a direct indication of the corrosivity of the local environment for a given alloy. In contrast, the second identifies environments in which dissimilar-material coupling may promote galvanic attack [3]. The manufacturer's reviewed documentation confirms that both sensor types are implemented in the aircraft-qualified integrated suite and that cumulative charge metrics are recorded to support long-term severity assessment [6,7,19,20].

Piezoelectric PZT transducers and eddy-current sensors complemented the core corrosion-monitoring set as higher-level follow-up diagnostics. Piezoelectric transducers are well established in SHM because they can operate as both actuators and receivers, enabling impedance- and guided-wave-based diagnostics of local stiffness changes, disbonding, loosening, and damage growth [4,8,9,21]. In the proposed architecture, their role is to localize subregions where persistent corrosion-prone conditions may already have led to corrosion-related structural degradation. Eddy-current sensors, in turn, provide a robust electromagnetic means of tracking local changes in electrically conductive materials and are especially valuable for surface and near-surface discontinuities, thickness reduction, and damage evolution in metallic structures. Recent work has also shown that flexible eddy-current arrays can withstand harsh aircraft service environments, while aircraft-oriented electromagnetic and automated inspection studies support their usefulness as a complementary follow-up sensing layer in aviation structures [4,5,10,23,24]. In the present concept, eddy-current sensing is intended to provide local verification and follow-up monitoring of metallic degradation once a suspect subregion has been identified.

### *2.3. Sensor Installation in Underfloor and Closed Zones*

The installation strategy was based on the assumption that the underfloor space was the primary critical zone. Sensors were therefore prioritized for the lowest fuselage regions and for locations where liquid migration and retention were most likely, including floor-panel joints, riveted interfaces, fastening regions, penetrations, and local structural discontinuities. The objective was not merely geometric coverage but rather representation of the most aggressive local microenvironments within the closed compartment [1,2].

Different sensor groups were assigned distinct diagnostic roles. The air temperature/relative humidity sensor, surface temperature sensor, surface conductance sensor, free-corrosion sensor, and galvanic-corrosion sensor were used to continuously monitor the local microclimate and electrochemical activity and to provide an early-warning indication of corrosion-prone conditions. PZT transducers were intended to interrogate structural subregions where persistent warning states suggest that corrosion-related degradation may already be affecting local stiffness or guided-wave propagation. Eddy-current sensors were considered for areas where corrosion may cause measurable metal loss, geometric discontinuities, or subsurface degradation in conductive components and, in the staged framework proposed here, are intended to support local verification and monitoring of damage growth [3-5,8-10,23,24].

### *2.4. Data Acquisition During Operation*

The monitoring concept was based on in-service data acquisition rather than on laboratory-only or post-maintenance observations. This choice was essential because atmospheric corrosion conditions in aircraft strongly depend on actual mission histories, operational states, thermal transitions, and contamination events. TM0416-2016 explicitly emphasizes the value of continuous electrochemical and conductance records over time, since they capture the temporal variability of corrosion-related conditions that occasional inspections alone cannot resolve [3].

For the underfloor compartment, data acquisition was intended to capture not only flight and parking conditions but also events typical of medical helicopter operations, such as patient transport, onboard medical activity, cleaning, and decontamination. Each signal was therefore treated as a time series tied to a specific location and exposure history. In this way, data acquisition served as the first stage of a broader decision-support chain: sensing, local storage, data retrieval, signal analysis, and maintenance-oriented interpretation consistent with condition-based operation [1,3,7].

### *2.5. Data Preprocessing and Feature Extraction*

After retrieval, the raw sensor data underwent preprocessing that included completeness checks, time-stamp synchronization, identification of missing or nonphysical records, filtering of short-term disturbances, and segmentation of the signals into intervals representing distinct operational states. This stage was not treated as merely a technical data-cleaning step; rather, it was regarded as the basis for maintenance-relevant interpretation within a condition-based philosophy [1,3].

The extracted features were intended to answer a maintenance-relevant question: whether the monitored closed zone should continue to be observed, whether access should be scheduled, or whether additional follow-up diagnostics should be initiated. For this reason, the analysis considered not only instantaneous values but also the persistence of unfavorable states over time. The resulting feature set included descriptors of relative humidity, air and surface temperatures, surface conductance as an indicator of contamination and electrolyte formation, free-corrosion and galvanic-corrosion signals, and the duration each state remained above predefined levels. This approach allowed short-lived transient events to be distinguished from sustained aggressive microclimatic conditions [2,3,6,7].

The adopted interpretation held that relative humidity alone is insufficient to define a corrosion-relevant state. Instead, the local microclimate and atmospheric corrosivity of the closed zone were assessed based on the combined behavior of humidity, contamination-related surface conductance, electrochemical activity, and state duration. In other words, a high-humidity episode without electrolyte formation or electrochemical response was not considered equivalent to a sustained state marked by elevated conductance and measurable free or galvanic corrosion signals. Importantly, the threshold values used in this study were not interpreted as direct damage thresholds. Instead, they were treated as transferable screening thresholds for early warning of corrosion-prone conditions. Their role was to indicate that the monitored zone had entered a state which, if sustained over longer periods, could favor the initiation and development of corrosion. In this interpretation, the environmental and electrochemical channels provide an early indication of risk, whereas direct confirmation and localization of corrosion-related damage are addressed by the higher-level follow-up sensing layers [2,3].

In the proposed operational implementation, the feature vector is processed by an AI-assisted decision layer that combines multi-parameter trend recognition, persistence analysis, previously developed pattern-recognition algorithms, and rule-based maintenance logic. In this paper, the term AI-assisted refers to a supervisory software layer in which abrupt increases in humidity, persistent high-wetness states, conductance excursions, and corrosion-current activity are first identified from synchronized time series and then compared against a library of previously stored warning patterns. A GPT-type language model serves as an interpretive support module to contextualize the detected pattern, formulate a human-readable alarm, and associate the event with a predefined maintenance recommendation in the service system. Its role is therefore supportive rather than autonomous: it does not authorize maintenance actions on its own, but helps convert fused sensor information into an operationally understandable message for helicopter maintenance personnel. The AI-assisted layer takes synchronized multi-sensor features and persistence descriptors as input and returns an alert class together with a recommended maintenance action. The same architecture can be tuned to different sensitivity settings: a conservative configuration to reduce nuisance alarms, a nominal configuration for routine operation, and a high-sensitivity configuration for periods of elevated mission load, known fluid contamination, or increased corrosion concern [11-18].

### *2.6. Multi-Sensor Data Fusion and Warning Logic*

The final stage of the methodology consisted of combining information from the available sensing layers into a hierarchical warning and follow-up logic. The central assumption was that the first-stage sensing layer, composed of environmental, conductance, and electrochemical channels, should provide early warning of corrosion-prone conditions, whereas the subsequent sensing layers should provide progressively more specific diagnostic information once persistent alarms are observed. No single sensor class can provide the full decision-relevant picture in isolation [2-5].

In the first stage, air temperature, relative humidity, surface temperature, surface conductance, free-corrosion signals, and galvanic-corrosion signals were fused to identify whether the local microclimate and electrochemical state of the monitored zone were conducive to long-term corrosion development. Temperature and humidity were treated as background descriptors, surface conductance as an indicator of electrolyte formation and contamination severity, and the electrochemical channels as the strongest confirmation that the environment had become corrosion-prone. In this interpretation, these variables do not constitute direct proof of structural corrosion

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damage. Rather, they indicate that the local conditions are becoming sufficiently severe and persistent to justify increased surveillance, preventive action, or follow-up inspection [3,6,7].

In the second stage, PZT sensing is intended to localize the subregion most likely affected by corrosion-related degradation. Owing to the direct and converse piezoelectric effects, PZT elements can both excite and sense elastic waves or operate in an electromechanical impedance mode. Any local change in stiffness, bond condition, looseness, material continuity, or corrosion-induced degradation alters the wave response and/or impedance signature relative to a baseline state. In the proposed framework, persistent warning states from the first-stage sensing layer trigger PZT interrogation, whose role is to identify areas where the structure deviates from its reference condition and where corrosion may already have initiated or begun to affect local structural behavior [4].

In the third stage, eddy-current sensing is used for local verification and follow-up monitoring of metallic degradation. When alternating current flows through the probe coil, it generates a time-varying magnetic field that induces eddy currents in the conductive substrate. These induced currents generate a secondary magnetic field that modifies the impedance of the sensing coil. Corrosion-induced material loss, pitting, cracking, subsurface discontinuities, or changes in lift-off alter the eddy-current distribution and, consequently, the measured amplitude and phase response. Once a suspect region has been identified, eddy-current sensing is intended to assess whether material loss or corrosion-related discontinuities are present and to monitor their growth over time [5].

Within this hierarchy, the environmental and electrochemical channels define the overall corrosion-prone state of the monitored zone, PZT sensing narrows the assessment to the most suspect structural subregion, and eddy-current sensing provides local confirmation and follow-up observation at a specific conductive detail. This last function is particularly relevant for hybrid interfaces, fastening regions, and local joints between composite panels and the aluminum helicopter structure, where corrosion may initiate in a highly localized manner and then evolve under repeated service exposure.

For maintenance integration, the warning logic was linked to action-oriented response classes. A Watch state is intended to increase trend surveillance without immediate structural opening. A Warning state is intended to trigger targeted inspection at the next suitable maintenance opportunity, open the hatch for compartment airing when justified, and verify drainage paths, seals, and possible routes of fluid ingress. A Severe state is intended to produce a direct alarm in the maintenance-support interface, justify opening the closed zone, initiate local drying or wipe-down if trapped moisture is present, and trigger PZT-based localization together with local eddy-current verification at the most vulnerable metallic details. In this way, the fused sensing architecture supports maintenance decisions that are progressively based on measured structural condition rather than on fixed service intervals alone [1,11-18].

On this basis, the warning logic was formulated as a multi-level scheme. A low state indicated the absence of persistent environmental and electrochemical evidence of corrosion-prone conditions. An intermediate state indicated the presence of an unfavorable microclimate, but without structural confirmation. A high-warning state was assigned when corrosive environmental conditions persisted over time and electrochemical activity was detected, thereby justifying escalation to the follow-up diagnostic layers. Such a fusion-based interpretation enables rational condition-based maintenance by reducing unnecessary floor-panel removals and directing inspections and corrective actions toward locations that exhibit genuinely elevated long-term corrosion risk or incipient hidden damage. The practical mapping between alert levels and representative maintenance actions is summarized in Table 1 [1-5,11-18].

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**Table 1.** Alert level vs maintenance action in the proposed maintenance-support logic.

| Alert level | Indicative condition | Maintenance action | Typical crew/system instruction |
|---|---|---|---|
| Watch | Short or mild increase in humidity/wetness; no persistent structural confirmation. | Continue observation and review trends; no immediate opening required. | Keep the zone under surveillance; optionally open the hatch for airing at a convenient service opportunity. |
| Warning | Persistent rise in RH/conductance and/or intermittent corrosion activity. | Plan targeted inspection and preventive drying/cleaning at the next suitable maintenance opportunity. | Open the hatch, air out the compartment, check the drains and seals, and dry any visible moisture if present. |
| Severe | Near-saturated humidity, high conductance, persistent electrochemical activity, or repeated long-duration events. | Immediate intervention with local follow-up diagnostics. | Open the hatch promptly, remove trapped liquid, dry or wipe the area with a clean cloth if necessary, then trigger PZT localization and EC/NDT verification. |

## 3. Results

This section focuses on Sensor sets 1 and 2, which represent the two most informative horizontal installations in the in-service test campaign. Sensor set 1 was installed beneath the cabin floor in a closed under-floor zone, whereas Sensor set 2 was installed below the main gearbox in a horizontal configuration. Their schematic locations on the air medical helicopter are shown in Figure 1. Sensor set 1 captured prolonged episodes of under-floor wetness, while Sensor set 2 recorded the clearest condensation-driven activation sequence. Figure 1 provides the spatial context for the results discussed in Sections 3.1-3.4, including the contrast between a closed under-floor warning case (Sensor set 1) and a representative condensation-driven response near the main gearbox (Sensor set 2). However, a reliable interpretation of these results also requires supplementary contextual information, including even basic flight-operation data, such as when and how the helicopter was operated, its typical flight profiles, mission frequency, and flight altitudes, together with meteorological data from nearby weather stations. Such information enables reconstruction of the environmental and operational conditions to which the helicopter was exposed and identification of the factors influencing conditions observed in enclosed helicopter zones, particularly beneath the cabin floor. On this basis, increased moisture levels and other signals detected in the under-floor area may be attributed not only to ambient humidity and temperature effects but also to liquid ingress or floor contamination from operational fluids, including water, blood, or other agents used during life-saving missions.

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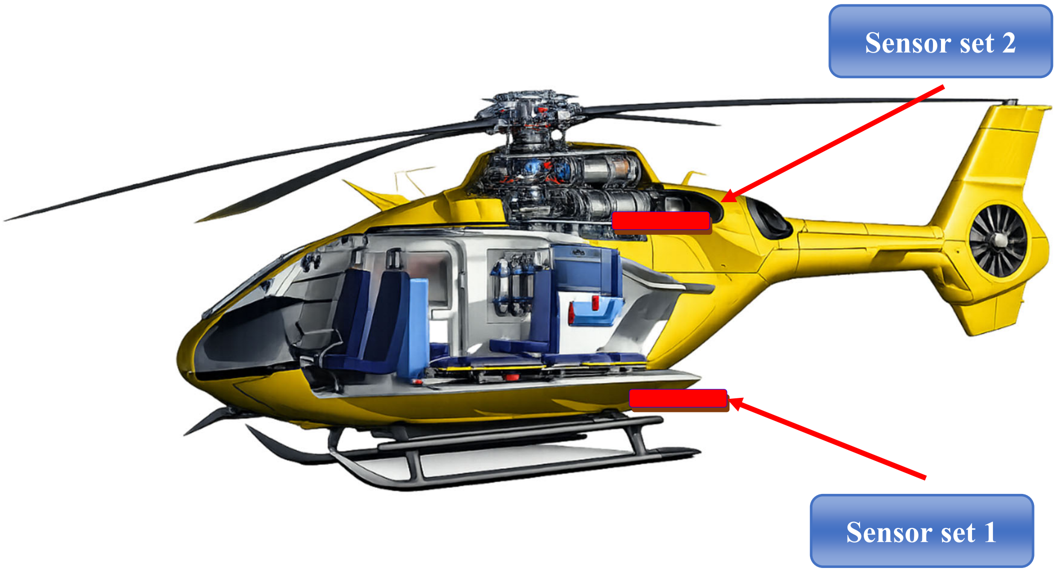

**Figure 1.** Schematic location of Sensor set 1 and Sensor set 2 on the medical helicopter. Sensor set 1 was installed beneath the cabin floor in a closed under-floor zone, whereas Sensor set 2 was installed below the main gearbox in a horizontal configuration.

This location figure provides the spatial context for the results discussed in Sections 3.1-3.4, including the contrast between a closed under-floor warning case (Sensor set 1) and a representative condensation-driven response near the main gearbox (Sensor set 2).

### *3.1. Sensor Deployment Feasibility*

Both sensor sets remained operational throughout the in-service campaign, from 24 January 2026 to 16 April 2026, with 3935 records for Sensor set 1 and 3938 for Sensor set 2. The median sampling interval was 30 min for both sets; the maximum observed gaps were 35.0 min for Sensor set 1 and 33.8 min for Sensor set 2; and 99.87% / 99.90% of intervals fell within 30 ± 5 min for Sensor sets 1 and 2, respectively. These values confirm that autonomous data logging was feasible for long-duration helicopter operations without significant loss of continuity.

The signal range was also sufficient for structural health monitoring (Figure 2). Sensor set 1 covered RH = 21.4–100.0%, air temperature = −10.9 to 24.7 °C, Cond Lo = 0.005–1.0 μS, and Cond Hi = 5.0–241.4 μS. Sensor set 2 covered RH = 6.6–98.7%, air temperature = −11.7 to 47.5 °C, Cond Lo = 0.005–1.0 μS, and Cond Hi = 5.0–1894 μS. The repeated returns to the dry-state baseline (Cond Lo ≈ 0.005 μS) after wet episodes show that the sensor sets did not remain artificially latched in a high-wetness state.

**Table 2.** Summary of signal continuity and final corrosion totals for the two focus sensor sets.

| Sensor | Records | Median interval | Max gap | Final totals |
|---|---|---|---|---|
| Sensor set 1 | 3935 | 30 min | 35.0 min | Tot Free 0.007995 C; Tot Galv 0.002231 C |

| | | | | |
|---|---|---|---|---|
| Sensor set 2 | 3938 | 30 min | 33.8 min | Tot Free 0.001381 C; Tot Galv 0.002103 C |

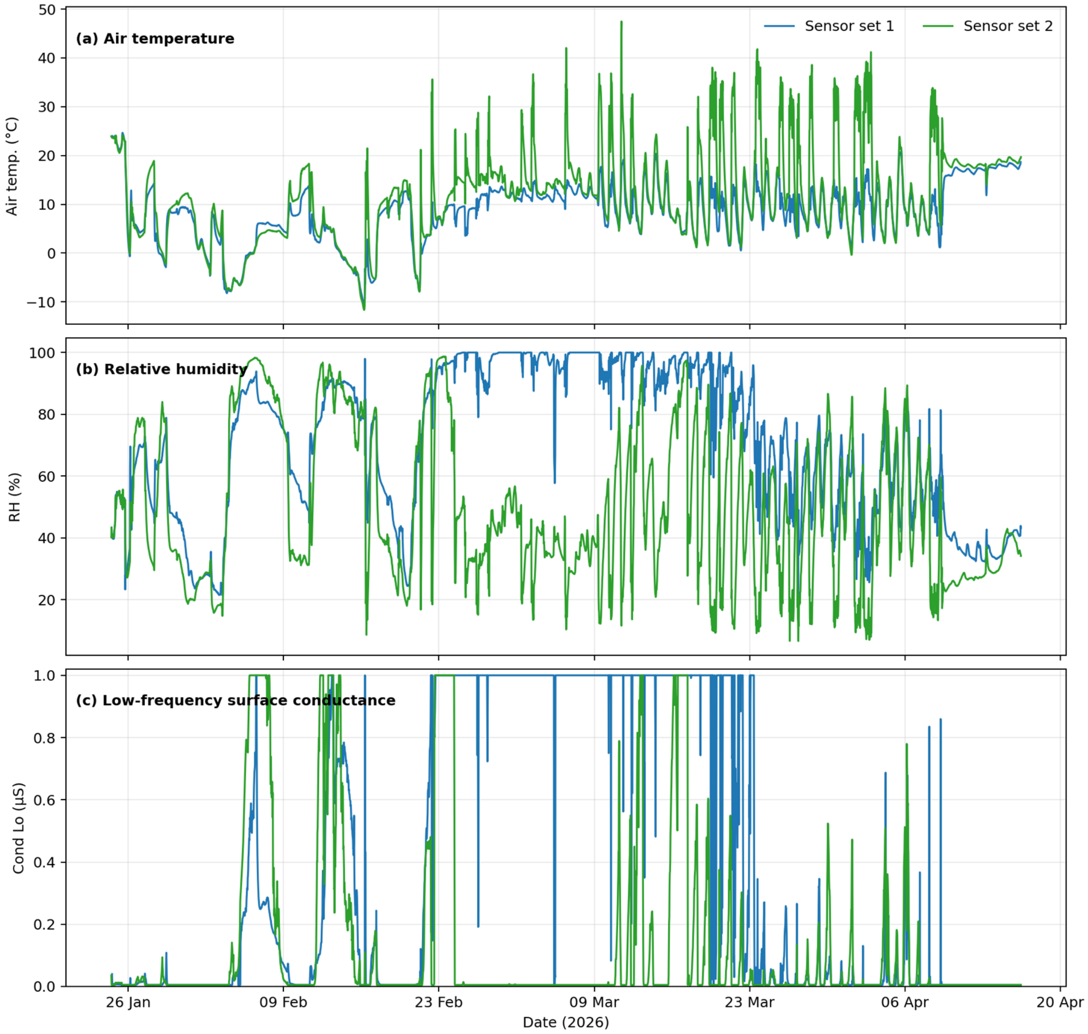

**Figure 2.** Full-campaign signals for Sensor set 1 and Sensor set 2: (a) air temperature, (b) relative humidity, and (c) low-frequency surface conductance. Continuous operation for ~82 days, with repeated returns to the dry-state baseline, demonstrates that autonomous deployment was feasible under in-service helicopter conditions.

### *3.2. Representative In-Service Signals*

The two sensor sets captured two distinct classes of in-service response (Figure 3). Sensor set 2 exhibited a classic condensation-driven activation sequence. Between 5 and 14 February 2026, RH increased from dry conditions to sustained levels of 80–90%, while Cond Lo rose from the dry baseline to values approaching 1.0 µS. The dominant galvanic-corrosion episode occurred from 7 February 14:50 to 8 February 08:20, lasted 18 h, and accumulated 0.001066 C, i.e., 50.7% of the final total galvanic charge. The dominant free-corrosion episode followed from 12 February 00:20 to 13 February 12:50, lasted 37 h, and accumulated 0.000798 C, i.e., 57.8% of the final total free-corrosion charge. This pattern is consistent with the gradual build-up of a persistent electrolyte film on the horizontal surface below the gearbox.

In contrast, Sensor set 1 exhibited a much more persistent under-floor wetting signature. Over the full campaign, it reached Tot Free Corr = 0.007995 C, far above Sensor set 2 (0.001381 C), while its galvanic total remained comparable to the gearbox-floor sensor (0.002231 C vs. 0.002103 C). The dominant free-corrosion episode on Sensor set 1 occurred from 22 February 12:09 to 24 February 10:39, lasted 47 h, and contributed 0.002710 C, i.e., 33.9% of the final free-corrosion charge. The dominant galvanic episode occurred from 27 February 14:39 to 28 February 08:39, lasted 18.5 h, and contributed 0.000907 C, i.e., 40.7% of the final galvanic charge.

A particularly informative event was recorded on 18 March 2026, when Sensor set 1 remained near RH = 98–100% and its conductance proxy increased rapidly to Cond Hi = 241.4 µS, whereas the other sensors in the aircraft simultaneously dropped to roughly 19–35% RH by about 09:00. According to the operational notes accompanying the analysis, these abrupt excursions occurred during flight missions and dropped rapidly after the floor access hatch was opened. Taken together, the signal shape is more consistent with localized liquid ingress or trapping beneath the floor than with ambient environmental humidity alone. In an air-medical helicopter, accidental spillage or leakage of transported fluids is a plausible explanation, but the present sensor set does not directly identify the fluid chemistry.

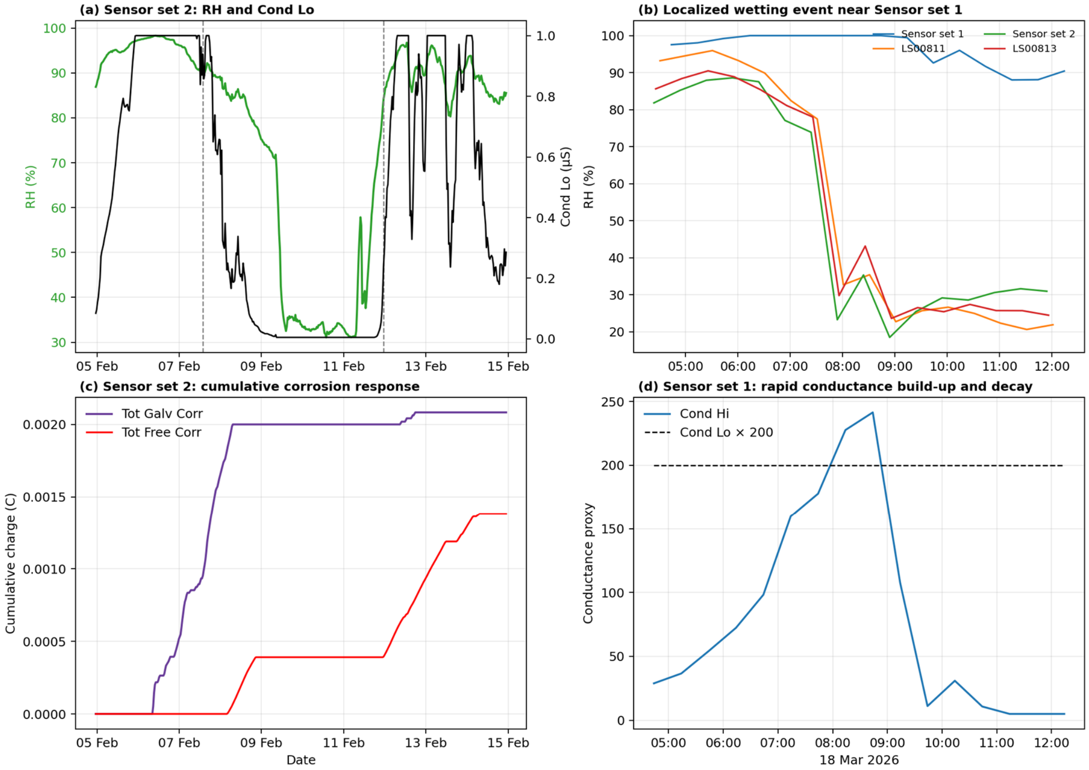

**Figure 3.** Representative in-service signals. (a, c) Sensor set 2 during the February condensation-driven activation sequence, showing RH and Cond Lo build-up followed by galvanic and free-corrosion accumulation. (b, d) A localized wetting event occurred near Sensor set 1 on 18 March 2026, during which RH remained near saturation, and conductance rose sharply, while the other aircraft sensors simultaneously dried out.

**Table 3.** Dominant in-service corrosion episodes captured by Sensor set 1 and Sensor set 2.

| Sensor | Dominant mechanism | Time window | Duration | Charge | Share of final total |
|---|---|---|---|---|---|
| Sensor set 2 | Galvanic | 07 Feb 14:50 – 08 Feb 08:20 | 18 h | 0.001066 C | 50.7% |

| | | | | | |
|---|---|---|---|---|---|
| Sensor set 2 | Free | 12 Feb 00:20 –<br>13 Feb 12:50 | 37 h | 0.000798 C | 57.8% |
| Sensor set 1 | Free | 22 Feb 12:09 –<br>24 Feb 10:39 | 47 h | 0.002710 C | 33.9% |
| Sensor set 1 | Galvanic | 27 Feb 14:39 –<br>28 Feb 08:39 | 18.5 h | 0.000907 C | 40.7% |

### *3.3. Corrosion-Prone Condition Indicator*

The combined RH–conductance space offers a practical way to distinguish merely humid conditions from truly corrosion-prone conditions (Figure 4). Sensor set 2 is particularly useful for identifying onset behavior because it experienced the full transition from dry to wet to corrosive states without the pronounced under-floor liquid trapping observed on Sensor set 1. Considering only persistent episodes lasting at least 1 h, free corrosion on Sensor set 2 began at RH = 84.3–90.2% and Cond Lo = 0.245–0.830 μS, while galvanic corrosion began at RH = 85.7–98.2% and Cond Lo = 0.328–1.0 μS. By comparison, persistent activity on Sensor set 1 shifted toward higher wetness: free-corrosion episodes began at RH = 85.1–100% and Cond Lo = 0.585–1.0 μS, whereas galvanic episodes began only at RH = 92.5–100% and Cond Lo = 1.0 μS. This confirms that conductance, rather than RH alone, is the more direct indicator of an electrochemically active electrolyte film.

A conservative corrosion-prone condition indicator (CPCI) was therefore defined as RH ≥ 80% and Cond Lo ≥ 0.05 μS. This mild threshold captured 95.5% of free-corrosion activity and 100% of galvanic activity on Sensor set 2, and 98.8% of free-corrosion activity and 98.9% of galvanic activity on Sensor set 1. However, the indicator should be understood as a warning-oriented indicator of a corrosion-prone state rather than as a direct metric of corrosion damage, because many humid intervals did not produce measurable charge accumulation. In other words, CPCI is highly sensitive and suitable for use in warning logic, but it is not sufficiently specific to quantify corrosion severity on its own. Its primary purpose is to identify conditions that, if sustained, may promote the future initiation and development of corrosion. In this sense, the proposed threshold values are transferable as practical screening criteria for closed aircraft zones, although their numerical calibration may require adjustment for other aircraft types, installation locations, and service environments.

A stronger regime, defined here as RH ≥ 90% and Cond Lo ≥ 0.5 μS, corresponded to 133.5 h in Sensor set 2 and 627.0 h in Sensor set 1. This higher threshold captured most severe, long-lasting wet states, particularly in the closed under-floor volume, and therefore provides a practical escalation level for maintenance-oriented warning assessment. Its significance is prospective rather than confirmatory: it marks persistent exposure severity that may justify preventive intervention and activation of the higher-level diagnostic layers, but it does not by itself prove that structural corrosion damage is already present.

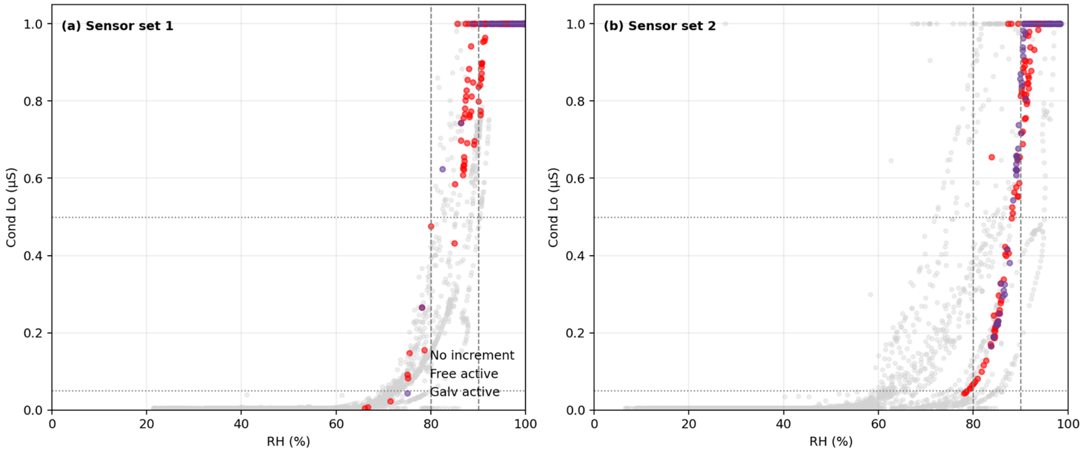

**Figure 4.** Empirical activation maps in RH–conductance space. Grey points indicate no increment in cumulative corrosion charge; red points indicate free-corrosion increments; purple points indicate galvanic-corrosion increments. Dashed lines show RH = 80% and 90%; dotted lines show Cond Lo = 0.05 and 0.5 µS. Sensor set 2 occupies a broader activation corridor, whereas Sensor set 1 corrosion increments are concentrated at near-saturated RH and high conductance.

### *3.4. Warning-Level Assessment for Closed Zones*

For closed or difficult-to-inspect aircraft zones, the data support a three-level warning logic based on the same RH–conductance framework: Watch = RH ≥ 80% and Cond Lo ≥ 0.05 µS; Warning = RH ≥ 90% and Cond Lo ≥ 0.5 µS; Severe = RH ≥ 95%, Cond Lo = 1.0 µS, and Cond Hi ≥ 20 µS. The severe state was defined to capture not only high humidity, but also a persistently conductive film with clear evidence of strong wetting or replenishment. From a maintenance perspective, the practical meaning of these thresholds is prospective rather than confirmatory. A Watch, Warning, or Severe state does not by itself prove that corrosion damage is already present. Instead, it indicates that the monitored zone has experienced sufficiently unfavorable and persistent conditions to justify increased surveillance, preventive action, and, when escalation persists, higher-level diagnostics.

When this logic was applied to the two focus sensor sets (Figure 4), Sensor set 2 spent 179.0 h in Watch, 82.0 h in Warning, and 51.5 h in Severe. It produced 6 warning episodes and 3 severe episodes longer than 6 h, with the longest warning episode lasting 52.5 h and the longest severe episode lasting 21.5 h. This is consistent with repeated, yet episodic, wetting below the gearbox.

The response of Sensor set 1 was substantially more critical. It spent 223.5 h in Watch, 220.5 h in Warning, and 406.5 h in Severe, and generated 20 warning episodes longer than 6 h and 14 severe episodes longer than 6 h. The longest warning episode lasted 96.0 h, while the longest severe episode lasted 70.5 h. These persistence times are too long to be explained by short ambient-humidity excursions alone and instead point to wetness retention within a closed volume, very likely associated with trapped liquid or repeated replenishment.

From a maintenance perspective, the key observation is that persistence matters more than peak amplitude in closed zones. Once the severe state has been sustained for several hours, inspection should not be limited to searching for corrosion products; it should also include verification of drainage paths, local ventilation, and potential routes for fluid ingress. In the proposed architecture, persistent severe states are intended to trigger PZT-based localization of probable corrosion-affected subregions and eddy-current follow-up to verify and monitor local degradation growth. In the present case, the operational note that abrupt Sensor set 1 excursions occurred during flight missions further supports inspection for under-floor liquid ingress or spillage after severe alarms are registered.

Overall, the results show that Sensor set 2 is best suited for deriving the empirical corrosion-onset envelope, whereas Sensor set 1 is particularly valuable for warning-level assessment in closed aircraft zones. The combination of both signals demonstrates that CHM sensors can distinguish between broad humidity-driven corrosion risk and more critical local wetting events that require direct maintenance action.

When interpreted through the proposed AI-assisted maintenance layer, these results translate into different operational responses for the two focus locations. Sensor set 2 would predominantly support watch- or warning-type actions, including intensified trend review and targeted inspection planning, whereas Sensor set 1 would repeatedly escalate to severe alarms linked to direct maintenance intervention in the under-floor compartment. From the maintenance crew's perspective, the system's significance lies not only in indicating a hostile environment, but also in presenting a graded alarm that clarifies whether the appropriate response is continued observation, planned access and cleaning, or immediate opening and local follow-up inspection, as summarized in Table 1.

The same data also illustrate the practical role of sensitivity settings. With a lower-sensitivity configuration, only the longest and most persistent events would be escalated to maintenance alarms, which is useful when nuisance alerts must be minimized. With a higher-sensitivity configuration, shorter but repeated wetting episodes would be flagged for earlier inspection, which may be preferred for older aircraft, after contamination events, or in zones known to be particularly difficult to inspect. Such tunability is important for integrating the warning logic into an actual maintenance information system rather than treating it merely as an offline analytical tool [11,15-18].

### *3.5. PZT and Eddy-Current Follow-Up of Persistent Warning Episodes*

Although the present in-service campaign focused primarily on environmental, conductance, and electrochemical channels, the severe and long-duration events identified for Sensor set 1 define the most relevant time windows for higher-level follow-up diagnostics. In the proposed operational architecture, persistent warning states are first identified by the early-warning sensing layer and then passed to a second-stage diagnostic layer.

Within this staged framework, PZT sensing is intended to localize subregions in which corrosion-related degradation may already have initiated. Its role is not to identify the chemistry of corrosion directly, but to indicate where the local structural response deviates from the baseline and where a corrosion focus may already be affecting local mechanical behavior. Dziendzikowski et al. showed that PZT networks, interpreted within a transfer-impedance framework, are sensitive to local damage-related changes and can support path-based damage indication and localization [8]. Later work by Dziendzikowski, Kowalczyk, and co-authors showed that PZT-network decision logic should be corrected for environmental and operational variability, because temperature-driven drift may otherwise increase the false-call rate [9]. This broader line of work also supports the practical use of PZT-based SHM networks for localizing suspect regions in monitored structures, including container-like or enclosed technical systems [8,9,21]. In practical maintenance terms, PZT sensing is intended to indicate which subregion should be opened first or prioritized for closer follow-up.

Eddy-current sensing constitutes the subsequent verification and progression-monitoring layer. After a suspect subregion has been identified, eddy-current sensing is intended to confirm whether local metallic degradation is present and to monitor its growth over time. Multifrequency, aircraft-oriented eddy-current inspection has been shown to improve crack visibility and support the assessment of size, depth, and location in multilayer airframe structures [10]. Recent Applied Sciences studies have also demonstrated the usefulness of electromagnetic testing combined with machine learning for hidden aircraft corrosion detection and of automated eddy-current-capable inspection platforms for practical aviation NDT deployment [23,24]. In the context of the under-floor zone investigated here, such follow-up inspection would be particularly justified in fastening regions, lap-joint-like interfaces, penetrations, and hybrid joints between composite panels and the aluminum helicopter structure, where persistent wetness may promote localized corrosion or crack initiation. Accordingly, the proposed interpretation logic is hierarchical: the environmental and electrochemical channels provide early warning that corrosion-promoting conditions have persisted; PZT sensing localizes where corrosion-related structural degradation may already be present; and eddy-current sensing is then used to verify and monitor the growth of local metallic damage. This staged interpretation avoids overestimating the meaning of the first-stage warning thresholds while strengthening their practical relevance for maintenance decision support.

## 4. Discussion

### *4.1. Relevance for SHM and Predictive Maintenance*

The proposed multi-sensor approach is relevant to SHM because it extends monitoring beyond structural response to include the environmental and electrochemical conditions that promote corrosion in enclosed aircraft zones. This is particularly important in underfloor spaces, where direct inspection is limited and corrosion may develop unnoticed between scheduled maintenance actions. By combining humidity, temperature, surface conductance, and corrosion-related signals, the proposed framework provides a more realistic representation of the monitored zone's actual condition than any single-parameter observation [2,19,20].

From a predictive-maintenance perspective, the main advantage of the method is the earlier identification of conditions that may lead to hidden corrosion. This allows maintenance action to be taken before corrosion progresses to more advanced damage that requires repair. In practical terms, the monitoring output may inform decisions about whether the compartment should be opened, cleaned, inspected, or checked for drainage issues or fluid ingress. The method therefore supports preventive action against corrosion-promoting conditions rather than purely corrective action after damage has already occurred [19,20,22].

An important practical consequence is that closed zones need not be opened solely because a fixed maintenance interval has been reached. Instead, opening and cleaning may be performed when the measured condition indicates a persistent warning or severe state. This approach aligns with condition-based maintenance and may reduce unnecessary disassembly, maintenance effort, and aircraft downtime. In this sense, the proposed system supports maintenance planning by linking maintenance actions more closely to the monitored structure's actual exposure history [20,22].

The broader significance of the method is that it is not limited to aerospace structures. The same early-warning, localization, and follow-up philosophy can be transferred to civil engineering components and infrastructures that contain hidden or difficult-to-access zones, such as closed steel details, box sections, joints, anchorages, cavities, or other locations where moisture retention and delayed inspection may allow degradation to develop unnoticed. In that sense, the helicopter application should be viewed as a demanding real-world demonstrator of a more general SHM methodology based on universal sensing, persistence analysis, and staged diagnostic escalation.

### *4.2. AI-Assisted Maintenance Integration and Transition to Condition-Based Maintenance*

A particularly important practical extension of the proposed framework is to integrate fused sensor interpretation with an AI-assisted maintenance-support interface. In this implementation, the system would continuously classify the state of the monitored zone, issue a graded alert to helicopter maintenance personnel, and map each alert level to a predefined maintenance action. This transforms the monitoring architecture from a passive data logger into an active decision-support tool that helps maintenance staff determine whether the appropriate response is observation, a scheduled inspection, opening the hatch to air or dry the compartment, or immediate intervention [11-18,22]. In this paper, the AI-assisted layer should be understood as a supervisory interpretation module combining synchronized sensor features, persistence descriptors, previously developed pattern-recognition routines, and rule-based maintenance logic. A GPT-type language model is used as a support module to transform the detected event into a human-readable maintenance message and to associate it with a predefined recommendation; it does not autonomously authorize maintenance actions.

From an operational perspective, this logic is also important because it supports a gradual shift from resource-based maintenance to condition-based maintenance. Instead of opening hidden zones

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only when a fixed service interval is reached, the maintenance organization may use measured condition history, the persistence of warning states, and AI-assisted escalation logic to determine whether access can be deferred or accelerated. This does not eliminate maintenance intervals or engineering authority; rather, it provides additional evidence for adapting inspection timing to the helicopter's actual exposure history and the monitored compartment [1,11,15-18,20,22].

The decision-support logic proposed in this study is summarized schematically in Figure 5, which illustrates the sequence from multi-sensor acquisition and AI-assisted interpretation to alert generation, maintenance action, and localized follow-up inspection.

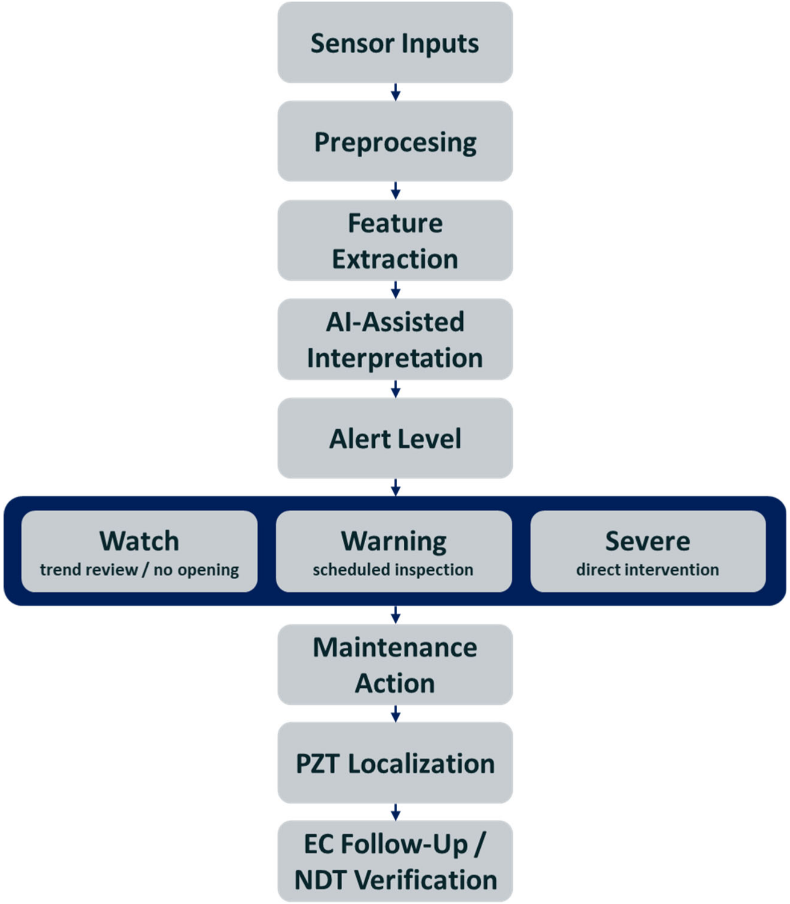

**Figure 5.** Block diagram of the proposed AI-assisted multi-sensor corrosion-warning and maintenance-support architecture for closed helicopter zones. Sensor inputs are first preprocessed and then feature-extracted. The fused feature set is interpreted by an AI-assisted decision layer, which assigns an alert level corresponding to maintenance actions. After alarm generation, PZT sensing localizes the most suspect structural subregion, while eddy-current sensing and targeted NDT provide local verification and follow-up assessment of degradation growth in critical metallic details.

The scheme integrates sensing, data interpretation, and maintenance decision support into a single operational workflow. In the first stage, sensor inputs from environmental and corrosion-related channels are acquired from the monitored helicopter zone and, after preprocessing and feature extraction, transformed into a fused representation of the local condition. This information is then interpreted by an AI-assisted layer that compares the current signal pattern with previously stored cases and applies threshold-based logic to recognize events such as abrupt increases in humidity, persistent surface wetness, or combined electrochemical responses. The resulting alert level is linked to maintenance actions, which may range from trend review to opening the hatch for ventilation and drying, local wipe-down cleaning, or more direct intervention. In the next stage, PZT sensing supports localization of the most suspect structural subregion, whereas eddy-current sensing and targeted NDT provide local verification and follow-up monitoring of degradation growth in critical metallic details.

### *4.3. Support for Targeted NDT*

The proposed approach is not intended to replace non-destructive testing. Its primary role is to support targeted NDT by identifying where and when detailed inspection is warranted. In hidden aircraft zones, this is especially valuable because direct access often requires removal of panels and other labor-intensive maintenance steps. The monitoring system can therefore serve as an early screening layer that helps prioritize compartments with elevated corrosion risk [23-25].

This support may improve inspection efficiency in two ways. First, if the monitored zone remains low risk, unnecessary opening of the structure can be avoided or postponed. Second, if warning or severe conditions are recorded, the same information may be used to direct NDT to the most relevant location and time window. Environmental and electrochemical signals define the general condition of the monitored zone. PZT sensing helps localize the most suspect subregion, and eddy-current sensing provides local confirmation and follow-up monitoring of degradation growth at a specific metallic detail, for example at a joint between a composite panel and the aluminum helicopter structure [8-10,23-25].

However, these sensing layers should still be treated as complementary tools. Final confirmation of damage and maintenance decisions should continue to rely on appropriate inspection methods, NDT procedures, and engineering assessment. Thus, the main contribution of the proposed system is improved targeting of NDT and maintenance actions, not the elimination of inspection [23-25].

### *4.4. Limitations and Practical Implementation Issues*

Several limitations should be emphasized. First, the proposed corrosion-prone condition indicator and the associated Watch/Warning/Severe thresholds are not direct measures of corrosion damage. They are early-warning criteria intended to identify conditions that, if sustained, may promote corrosion initiation and growth over longer periods. Second, although the threshold logic is transferable in the sense that the same physical interpretation can be applied to other closed aircraft zones, the numerical threshold values and persistence criteria may require recalibration for other aircraft types, structural details, installation locations, and service environments. The same qualification applies to potential civil engineering use: the methodology can be transferred conceptually to other infrastructure classes, but threshold calibration should still be performed for the specific material system, exposure scenario, and inspection strategy of the target structure.

Third, interpretation of the sensor response depends on the operational context. In the case analyzed here, understanding severe under-floor events may require additional information, such as mission history, weather conditions, and potential contamination by operational fluids. Without this context, distinguishing between condensation and local liquid ingress may be difficult. In addition, the current sensor set does not directly identify liquid chemistry, which limits a more detailed interpretation of the corrosion mechanism.

Fourth, the present in-service validation primarily concerns the early-warning layer based on environmental, conductance, and electrochemical sensing. The roles of PZT and eddy-current sensing are defined here as staged follow-up diagnostics: PZT sensing is intended to localize probable corrosion-affected subregions, while eddy-current sensing is intended to confirm and monitor local damage progression. Their full integration into a common operational workflow remains an important next step for future validation. Practical implementation also requires attention to sensor placement, long-term reliability, calibration of the AI layer, and integration with maintenance procedures. Because GPT-type and other LLM-assisted modules are best used as decision-support components rather than autonomous authorities, final maintenance actions should remain subject to validation data, human oversight, and engineering approval [17,18,22].

In real aircraft operation, complete end-to-end validation of corrosion-warning logic is difficult to achieve on a case-by-case basis. Hidden zones cannot be opened repeatedly without cost, downtime, and maintenance burden, and long-term corrosion evolution cannot be intentionally reproduced under operational conditions solely for validation purposes. For this reason, the present work should be regarded as a practically relevant intermediate validation stage: the early-warning thresholds are supported by in-service measurements and by qualitative field evidence showing that prolonged corrosive conditions in hidden zones may eventually lead to real, costly corrosion damage [19,20]. Further validation should progressively correlate warning episodes with direct inspections, PZT-based localization, eddy-current follow-up, and maintenance findings. The same practical limitation also applies to civil engineering assets with hidden or costly-to-access zones, where repeated intrusive opening for one-to-one validation may be technically possible but economically and operationally unjustified.

### *4.5. Field Inspection Evidence Supporting the Maintenance Relevance of Persistent Corrosion-Prone Conditions*

Although the warning logic proposed in this study is intentionally formulated as an early-warning framework rather than a direct damage-detection method, field inspection evidence supports its maintenance relevance. Figure 6 shows examples of corrosion observed in a hidden aircraft zone after prolonged exposure to moisture-retaining and corrosion-prone conditions. The damage was identified in riveted and lap-joint-type details representative of the kind of closed structural locations considered in the present monitoring concept.

These inspection findings support the practical interpretation of the warning thresholds adopted in this work. Persistent corrosive conditions, even if initially detected only through environmental, conductance, and electrochemical indicators, may evolve over longer periods into actual corrosion damage requiring costly corrective maintenance [19,20]. In the observed case, corrosion removal and repair were labor-intensive because they required access to a closed zone, removal of corrosion products, cleaning, restoration of protective layers, and local repair of affected elements. The photographs should therefore be interpreted as qualitative maintenance validation of the proposed warning logic: prolonged persistence of corrosion-prone conditions in hidden zones is not merely an environmental anomaly, but a practically important precursor that may eventually lead to real and costly structural degradation. This observation further justifies the use of staged follow-up diagnostics, in which persistent warnings trigger PZT localization and eddy-current monitoring of local damage growth.

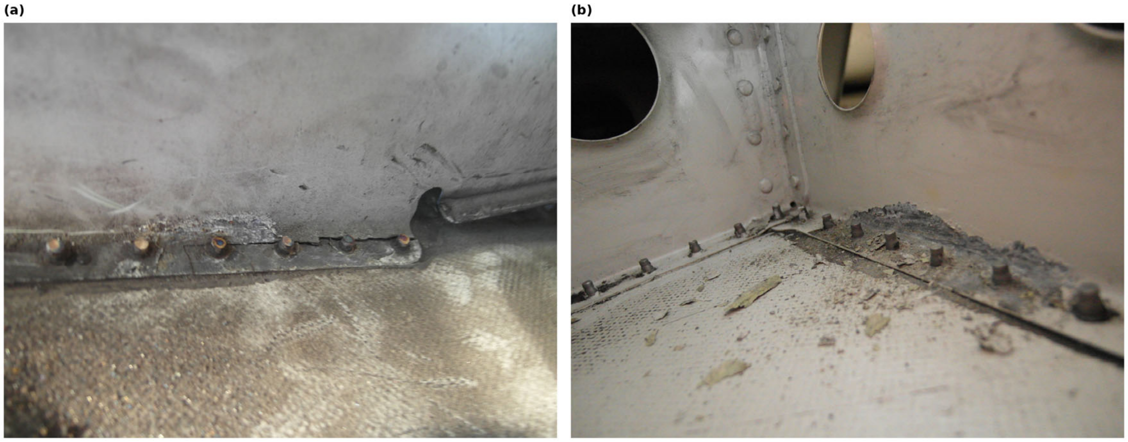

**Figure 6.** Field inspection evidence of corrosion in a hidden aircraft zone after prolonged persistence of corrosion-prone conditions. (a) Close-up view of corrosion damage developing along a riveted and lap-joint-type detail. (b) Wider view of corrosion products and degradation in a hidden structural zone. These findings

provide qualitative maintenance validation of the proposed early-warning logic: persistent corrosive conditions in closed zones may evolve into actual corrosion damage that is difficult and costly to remove and repair. The images therefore support the need for early warning, followed by PZT-based localization and eddy-current monitoring of local damage growth.

## 5. Conclusions

This study presented a multi-sensor data fusion approach for the early warning of corrosion-prone conditions in closed aircraft zones. The results showed that environmental, conductance, and electrochemical sensing can identify persistent unfavorable conditions in hidden compartments during aircraft operation and distinguish between general humidity exposure and more critical long-duration wetting events. Within the proposed architecture, these first-stage signals are interpreted as indicators of increased long-term corrosion risk rather than as direct proof of existing structural damage.

The proposed approach is useful from a maintenance perspective because it supports condition-based decision-making in areas where routine inspection is difficult. Environmental and corrosion sensors define the general condition of the monitored zone, PZT sensing is intended to localize the most suspect subregion where corrosion-related degradation may already be present, and eddy-current sensing is intended to verify and monitor degradation growth at a specific conductive detail, including hybrid joints between composite panels and the aluminum helicopter structure. Its practical value therefore lies in helping determine whether a closed zone should be monitored further, aired, dried, opened, cleaned, or inspected, rather than relying solely on fixed maintenance intervals.

Because complete case-by-case validation in operational aircraft is inherently limited by access, cost, and availability constraints, the present study should be regarded as a practically relevant intermediate validation stage toward a fully integrated corrosion-warning and follow-up monitoring framework.

At the same time, the system is not intended to replace operational NDT or engineering judgment. Its purpose is to support and better target inspection activities by identifying locations and periods of increased corrosion risk and by linking warning levels to maintenance actions within a maintenance-support system. Field inspection evidence of corrosion in hidden structural details further supports the maintenance relevance of this concept by showing that long-lasting corrosive conditions may eventually lead to damage that is difficult and costly to remove and repair. More broadly, because the underlying sensing logic, persistence-based warning concept, localization strategy, and staged NDT follow-up are platform-independent, the same methodology may also be adapted to civil engineering structures and infrastructures that contain hidden or difficult-to-inspect zones.

Overall, the proposed solution supports a shift from reacting to already developed corrosion damage to acting earlier on the basis of persistent corrosion-promoting conditions. Future work should focus on direct correlation between warning states, PZT and eddy-current results, opening-inspection findings, targeted NDT results, and maintenance records, together with refinement of threshold values, expansion of the warning-pattern library, and development of implementation procedures for maintenance organizations [11,15-18].

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