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

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Featured Application

The proposed monitoring system is intended for hidden and difficult-to-access aircraft zones, where a first-stage early warning of corrosion-prone conditions can support targeted inspection, local drying, cleaning, and maintenance planning. In this study, the in-service validation concerns the environmental, conductance, and electrochemical sensing layer installed on a medical rescue helicopter. PZT and eddy-current sensing are retained as higher-level follow-up diagnostics within the proposed hierarchy: they have been validated separately under laboratory or controlled conditions, but their installation on the flying helicopter has not yet been performed because the system has only recently entered operational use and additional aircraft instrumentation requires an approved maintenance-access window, dedicated downtime, and a justified operational trigger. The concept may inform other closed-zone monitoring applications, including civil engineering, but the numerical thresholds and sensor configuration require case-specific calibration.

Abstract

Identifying corrosion-prone conditions early is a major maintenance challenge in closed, hard-to-access structural zones. This paper reports an in-service validation of the first monitoring layer of a multi-sensor data fusion approach for early warning of such conditions in selected closed zones of a medical rescue aircraft. The work covers sensor selection, installation in restricted-access compartments, and analysis of data from helicopter operations. Environmental, conductance, and electrochemical channels are combined to identify persistent conditions favorable to long-term corrosion development and to assign warning levels linked to maintenance actions. The thresholds proposed here are empirical screening criteria from the 82-day campaign, not universal damage thresholds or proof of existing corrosion. PZT and eddy-current sensing are planned as follow-up diagnostic layers in the overall architecture. These technologies have been validated separately under laboratory or controlled conditions but were not installed on the flying helicopter during this initial period. Although persistent severe early-warning episodes were detected, they did not coincide with an approved maintenance-access window suitable for additional PZT/EC hardware installation. The present results therefore characterize the corrosion-prone environment and the likelihood of corrosion initiation, not the type, exact location, pit depth, mass loss, or crack initiation of actual damage. Field inspection evidence of corrosion

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Academic Editors: Hong Pan and Zhibin Lin

Received: 10 May 2026
Revised: 28 May 2026
Accepted: 5 June 2026
Published: 9 June 2026

in hidden zones supports the practical relevance of early warning, while full end-to-end validation of localization and damage-growth monitoring remains future work.

Keywords: multi-sensor data fusion; structural health monitoring; corrosion-prone conditions; early warning; condition-informed maintenance; medical rescue aircraft; PZT sensing; eddy-current testing; hidden structural zones; maintenance decision support

1. Introduction

Corrosion is one of the most persistent degradation mechanisms affecting aircraft throughout their service life [1]. Beyond material loss, it can impair structural integrity, accelerate secondary damage, raise inspection costs, and reduce fleet availability [1,2]. Within a damage-tolerance framework, aircraft may operate with defects only within defined safety limits, so tracking damage initiation between scheduled inspections is essential [2]. Identifying unfavorable corrosion-related conditions early gives the best chance of stopping a local physicochemical process before it becomes a structurally significant defect [2,3].

Closed, difficult-to-access zones—underfloor spaces and enclosed structural compartments—present a distinct challenge because direct inspection access is limited [3]. These locations accumulate moisture, condensation, salts, and operational contaminants, producing local microclimates that differ substantially from the surrounding ambient [3,4]. Early-stage corrosion can therefore go undetected for prolonged periods and become apparent only after substantial progression. The problem is compounded by current trends in aerospace materials—chromate-free coatings and hybrid structural configurations—which alter corrosion behavior and complicate interpretation of in-service degradation [3,5].

Structural Health Monitoring (SHM) provides a useful framework for observing structural condition during operation, but traditional aerospace SHM has focused mainly on loads, fatigue, crack propagation, and damage detection, with limited attention to corrosion-promoting conditions [4]. Corrosion Health Monitoring (CHM) extends SHM to cover environmental and electrochemical precursors of corrosion initiation and development [4,5]. Parameters such as temperature, relative humidity, surface wetness, and free or galvanic corrosion currents are especially relevant here: combined, they give a more complete picture of the local corrosion environment than any single channel alone [5,6].

Engineering studies have demonstrated that compact autonomous sensors can collect in-service data on corrosion-prone conditions in selected aircraft structural zones [2,6,7]. The sensing problem is multidimensional: it requires not only selecting suitable sensors but also identifying representative installation locations, accommodating structural and operational constraints, and interpreting heterogeneous data streams from flight operations [2,6,7]. Corrosion-related phenomena also vary significantly across compartments and sensor locations, which makes multi-point, multi-parameter monitoring necessary in hidden aircraft zones [3,6,7].

The core challenge is not measuring individual variables but converting raw multi-channel observations into an actionable assessment of corrosion-prone conditions [6,7]. Single-parameter thresholding is often insufficient in structurally constrained aircraft zones, where adverse conditions arise from the combined effect of multiple environmental and operational factors. Multi-sensor data fusion, signal preprocessing, feature extraction, and AI-assisted decision support are therefore needed to integrate heterogeneous measurement channels into a warning-oriented framework [7–16]. This direction matches the broader shift in SHM toward data-driven monitoring that can improve inspection planning in areas where direct access is restricted [4,7,12,13,16,17].

Machine-learning methods are increasingly applied in SHM and corrosion monitoring to combine heterogeneous sensor features, classify damage states, predict degradation trends, and support inspection planning [12,13,16,18]. Common approaches in aerospace and infrastructure SHM include supervised classifiers, random forests, and convolutional or recurrent neural networks, particularly where direct experimental data are limited [12,13]. In adjacent engineering fields, CFD-generated data combined with optimized convolutional neural networks have been used to build fast surrogate models for complex coupled fields, showing how physics-based simulation and learning algorithms can extend sparse experimental observations [19]. Recent machine-learning-guided screening workflows similarly illustrate how data-driven models can explore large, high-dimensional parameter spaces when reliable training data are available [20]. These developments point toward virtual corrosion-scenario generation and threshold optimization in the longer term. The present 82-day two-location campaign is not, however, sufficient to train and validate a robust autonomous ML classifier; the warning logic here is therefore deterministic and threshold-and-persistence-based, while data-driven models are left for future work.

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 experimentally validated part of the contribution is deliberately focused on the first-stage monitoring layer: selection and installation of environmental, conductance, and electrochemical sensors in restricted-access and underfloor structural zones, processing of in-service measurement data, and formulation of a persistence-based warning logic for corrosion-prone conditions [6,7]. The paper therefore does not claim direct field validation of corrosion localization or damage-growth monitoring. Instead, it embeds the first-stage warning output in a staged diagnostic concept in which persistent alarms may, when operationally justified, trigger PZT-based localization and eddy-current or NDT-based verification. The PZT and eddy-current elements are supported by prior laboratory and controlled validation studies [17,18,21–23], but their installation on the flying helicopter remains a subsequent implementation step. The transferability discussed in this paper refers primarily to the monitoring logic—early warning, persistence assessment, and staged follow-up—not to the direct transfer of numerical thresholds across aircraft types or to civil engineering structures without recalibration.

2. Materials and Methods

The methodology was developed to provide early warning of corrosion-prone conditions in selected closed zones of a medical rescue helicopter. It comprised six stages: identification of critical closed structural zones, selection of an integrated sensor set, definition of complementary SHM/NDT follow-up layers, development of an installation strategy for underfloor and restricted-access compartments, in-service data acquisition, signal preprocessing and feature extraction, and multi-source data fusion to derive a corrosion-prone condition indicator and warning level. The in-service data and validation reported here cover the first-stage environmental, conductance, and electrochemical layer. PZT and eddy-current elements are planned follow-up diagnostics within a condition-informed maintenance-support framework, not fully validated operational outputs of this campaign [1,2,16].

2.1. Closed-Zone Corrosion Risk in Medical Rescue Aircraft

The most critical corrosion-prone zone was identified as the underfloor space of the medical cabin. The aircraft corrosion literature consistently identifies hidden, poorly ventilated, and difficult-to-access compartments as vulnerable to moisture accumulation, contaminant retention, and undetected corrosion progression. Underfloor regions are especially problematic because limited inspectability combines with strong potential for long-term electrolyte retention, which favors localized and crevice-type corrosion [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 the primary drivers of corrosion initiation and propagation identified in aircraft corrosion research [1,2].

Direct inspection of this zone requires removing floor panels—a labor-intensive process that typically withdraws the helicopter from service for a period. Continuous, indirect monitoring is therefore well-suited here: it can indicate whether inspection is necessary and whether floor removal can be deferred within a condition-based maintenance strategy [1].

2.2. Sensor Suite Selection

Reliable corrosion assessment cannot rely solely on observing already developed damage. It requires combining information on environmental severity, electrolyte presence, surface contamination, and electrochemical activity, with structural consequences detectable by SHM/NDT methods as a complementary layer. Recent reviews confirm that no single sensing category is sufficient to 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].

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].

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].

PZT transducers and eddy-current sensors are included as higher-level follow-up diagnostics in the proposed architecture. PZT transducers are well established in SHM as both actuators and receivers, enabling impedance- and guided-wave-based diagnostics of stiffness changes, disbonding, loosening, and damage growth [4,17,21]. Eddy-current sensors offer robust electromagnetic tracking of local changes in conductive materials, useful for surface and near-surface discontinuities, thickness reduction, pitting-related material loss, and crack-like defects [4,5,18,22,23]. Both layers have been validated separately in laboratory and controlled studies. They were not installed on the flying helicopter during the initial operating period—installing additional sensors on a real aircraft requires access, airworthiness coordination, downtime, and an operational justification—but they remain ready follow-up layers for deployment when a persistent warning state or scheduled maintenance opportunity makes installation viable.

The aircraft-qualified sensor suite used in the present study was selected for immediate deployability and flight-safety maturity. Nevertheless, several emerging sensing technologies are relevant for future generations of CHM systems in enclosed compartments. Flexible iontronic sensors exploit ionic dielectrics and electrical double layers to obtain high sensitivity, adaptability, durability, and reduced susceptibility to electromagnetic interference [24]. Bio-inspired ion-gating and iontronic neuromorphic concepts offer low-power adaptive signal processing at the sensor interface [25]. Multimodal artificial-skin and stretchable-sensor studies demonstrate how heterogeneous, conformable sensors can be combined with learning architectures for pattern recognition and perception-oriented data fusion [26,27]. Recent electret and heterointerface-based sensing concepts also show potential for resilient and adaptive perception under changing mechanical and environmental conditions [28]. These technologies are not yet direct replacements for aircraft-qualified corrosion-monitoring hardware, but they point toward future conformable, wireless or drift-mitigated, pH/chloride-sensitive, and thin-liquid-film sensing layers that could help distinguish condensation from mission-related fluids in closed helicopter zones.

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. These sensors characterize the environment and the likelihood that corrosion may initiate or progress; they do not directly identify the corrosion type, exact location, pit depth, mass loss, or crack initiation. PZT transducers and eddy-current sensors are therefore treated as follow-up layers. PZT sensing is intended to localize structural subregions where persistent warning states suggest that corrosion-related degradation may already have affected local stiffness or wave propagation. Eddy-current sensing is intended to verify and monitor local metallic degradation, including material loss or crack-like indications, once installation and access to the suspect region are available [3–5,17,18,21–23].

2.4. Data Acquisition During Operation

The monitoring concept relied on in-service data acquisition rather than laboratory-only or post-maintenance observations. Atmospheric corrosion conditions in aircraft depend strongly on actual mission histories, operational states, thermal transitions, and contamination events, and TM0416-2016 explicitly emphasizes the value of continuous electrochemical and conductance records over time for capturing temporal variability that occasional inspections cannot resolve [3].

For the underfloor compartment, data acquisition was designed to capture flight and parking conditions as well as events typical of medical helicopter operations: patient transport, onboard medical activity, cleaning, and decontamination. Each signal was treated as a time series tied to a specific location and exposure history, forming the first stage of a 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 were preprocessed: completeness checks, timestamp synchronization, identification of missing or non-physical records, filtering of short-term disturbances, and segmentation into intervals representing distinct operational states. This stage was treated as the basis for maintenance-relevant interpretation, not a routine data-cleaning step [1,3].

The extracted features were designed to answer a maintenance-relevant question: should the monitored zone continue under observation, should access be scheduled, or should follow-up diagnostics be triggered? The analysis therefore considered not only instantaneous values but also the persistence of unfavorable states. The feature set included descriptors of relative humidity, air and surface temperatures, surface conductance, free-corrosion and galvanic-corrosion signals, and the duration each state exceeded predefined levels. This allowed short-lived transient events to be distinguished from sustained aggressive microclimatic conditions [2,3,6,7].

Relative humidity alone does not define a corrosion-relevant state. The local microclimate and atmospheric corrosivity were assessed from the combined behavior of humidity, surface conductance, electrochemical activity, and state duration. A high-humidity episode without electrolyte formation or electrochemical response was not treated as equivalent to a sustained state with elevated conductance and measurable corrosion signals. The threshold values are screening criteria for early warning, not direct damage thresholds. Their role is to indicate that the monitored zone has entered conditions that, if sustained, could favor corrosion initiation. Direct confirmation and localization of damage are addressed by the higher-level follow-up sensing layers [2,3].

In the proposed operational implementation, alert assignment is deterministic and traceable. The input feature vector consists of synchronized descriptors—relative humidity, air and surface temperature, low- and high-frequency conductance, increments and cumulative values of free- and galvanic-corrosion response, and persistence descriptors for threshold exceedance—evaluated using rule-based threshold and persistence logic. As used in this paper, "AI-assisted" refers specifically to the maintenance-support interface surrounding this deterministic logic. A GPT-type language model serves only as a natural-language reporting module: it converts the detected event class, exceeded thresholds, episode duration, and predefined maintenance rule into a readable message for maintenance personnel. It does not perform untraceable feature fusion, authorize maintenance actions, or replace engineering judgment. Each generated recommendation must remain linked to the underlying sensor values, threshold identifiers, and rule base so that the alert is auditable and reproducible [8–15].

2.6. Multi-Sensor Data Fusion and Warning Logic

The final methodology stage combined information from the available sensing layers into a hierarchical warning and follow-up logic. The first-stage layer—environmental, conductance, and electrochemical channels—provides early warning of corrosion-prone conditions; subsequent layers provide progressively more specific diagnostic information once persistent alarms are registered. No single sensor class provides the full decision-relevant picture in isolation [2–5].

For traceability, a persistent episode was defined algorithmically rather than visually. An episode starts when all conditions assigned to a given alert level are satisfied in the synchronized time series. It ends when the same conditions are no longer satisfied for longer than one nominal sampling interval. Because the median sampling interval was approximately 30 min, events shorter than 1 h were treated as transient and were not used to define persistent corrosion-prone states. A single missing or isolated sub-threshold point not exceeding one nominal sampling interval may be merged with the adjacent episode if the threshold condition resumes immediately afterwards; longer interruptions define separate episodes. This definition was used to distinguish short environmental fluctuations from sustained wetness or electrochemical activity relevant for maintenance decisions.

In the first stage, air temperature, relative humidity, surface temperature, surface conductance, free-corrosion signals, and galvanic-corrosion signals were combined to assess whether the local microclimate and electrochemical state favored long-term corrosion development. Temperature and humidity served 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. These variables indicate that local conditions are becoming severe and persistent enough to justify increased surveillance or follow-up inspection; they do not constitute direct proof of structural corrosion damage [3,6,7].

In the second stage, PZT sensing is intended to localize the subregion most likely affected by corrosion-related structural degradation after a persistent warning state has justified follow-up diagnostics. 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 may alter the wave response and/or impedance signature relative to a baseline state. In the present in-service campaign, this stage was not yet deployed on the flying helicopter; it is a planned follow-up layer supported by prior laboratory and controlled validation work [4,17,21]. Therefore, the current manuscript treats PZT sensing as the next localization step after early warning, not as field-validated localization evidence from the 82-day campaign.

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 is intended to narrow the assessment to a suspect structural subregion, and eddy-current sensing is intended to provide local confirmation and follow-up observation at a specific conductive detail. Direct metrics such as pit depth, mass loss, crack initiation, or damage-growth rate cannot be derived from the currently installed environmental and electrochemical sensor sets alone. They require either physical inspection or a local NDT/eddy-current layer installed at the relevant detail. This distinction is particularly important 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.

The warning logic was linked to three action-oriented response classes. A Watch state increases trend surveillance without requiring structural opening. A Warning state triggers targeted inspection at the next maintenance opportunity, opens the hatch for airing when justified, and prompts verification of drainage paths, seals, and fluid-ingress routes. A Severe state raises a direct alarm, justifies opening the closed zone, initiates local drying or wipe-down if trapped moisture is present, and triggers PZT-based localization with local eddy-current verification at the most vulnerable metallic details. The fused sensing architecture thus supports maintenance decisions based on measured structural condition rather than fixed service intervals [1,8–15].

The warning logic has three levels. A low state indicates the absence of persistent environmental and electrochemical evidence of corrosion-prone conditions. An intermediate state indicates an unfavorable microclimate without structural confirmation. A high-warning state is assigned when corrosive conditions persist and electrochemical activity is detected, justifying escalation to the follow-up diagnostic layers. This fusion-based approach supports condition-informed maintenance planning by reducing unnecessary floor-panel removals and directing inspections toward locations and time periods with elevated long-term corrosion risk. It should not be interpreted as a complete prognostic CBM model, because the field data do not yet include remaining-useful-life estimates or direct damage-growth measurements. The mapping between alert levels and maintenance actions is summarized in Table 1 [1–5,8–15].

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.

https://doi.org/10.3390/app16125807

Table 1. *Cont.*

Alert Level	Indicative Condition	Maintenance Action	Typical Crew/System Instruction
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

Results focus on Sensor sets 1 and 2, the two most informative horizontal installations in the campaign. Sensor set 1 was installed beneath the cabin floor in a closed underfloor zone; Sensor set 2 was installed below the main gearbox. Their schematic locations are shown in Figure 1. Sensor set 1 captured prolonged underfloor wetting episodes; Sensor set 2 recorded the clearest condensation-driven activation sequence. Interpreting these results requires supplementary context, including basic flight-operation data (when and how the helicopter was operated, typical flight profiles, mission frequency, and flight altitudes) and meteorological data from nearby weather stations. This information allows reconstruction of the environmental and operational conditions during the campaign and supports attribution of increased moisture signals to ambient humidity, temperature effects, or liquid ingress from operational fluids such as water, blood, or other agents used during missions.

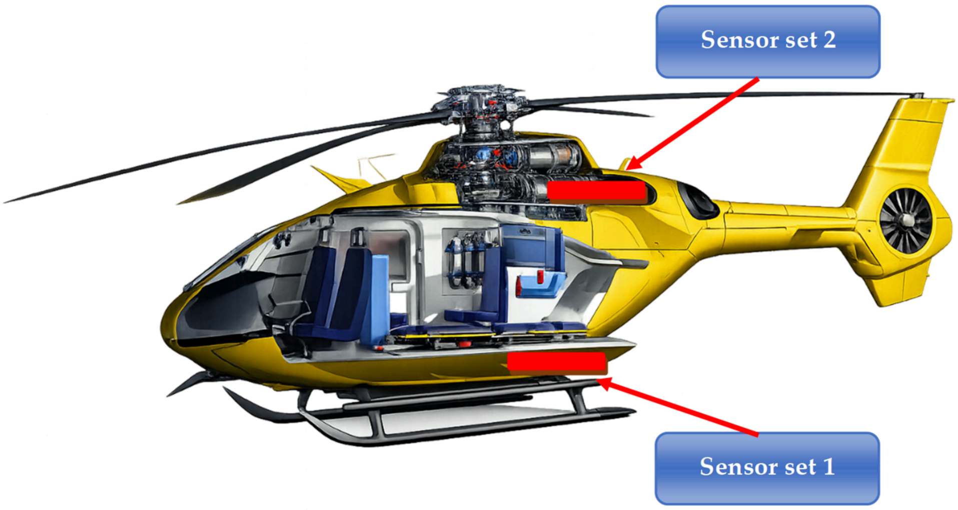

Figure 1. Schematic location of Sensor set 1 and Sensor set 2 on the medical helicopter. Sensor set 1 was installed beneath the cabin floor in a closed under-floor zone, whereas Sensor set 2 was installed below the main gearbox in a horizontal configuration.

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 campaign (24 January 2026 to 16 April 2026), recording 3935 records (Sensor set 1) and 3938 records (Sensor set 2). The median sampling interval was 30 min for both; maximum observed gaps were 35.0 min and 33.8 min, respectively; and 99.87%/99.90% of intervals fell within 30 ± 5 min for Sensor sets 1 and 2, respectively. Autonomous data logging was therefore feasible for long-duration helicopter operations without significant loss of continuity.

The signal ranges were sufficient for structural health monitoring (Figure 2). Sensor set 1: 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. Repeated returns to the dry-state baseline (Cond Lo ≈ 0.005 µS) after wet episodes confirm that the sensors did not remain artificially latched in a high-wetness state.

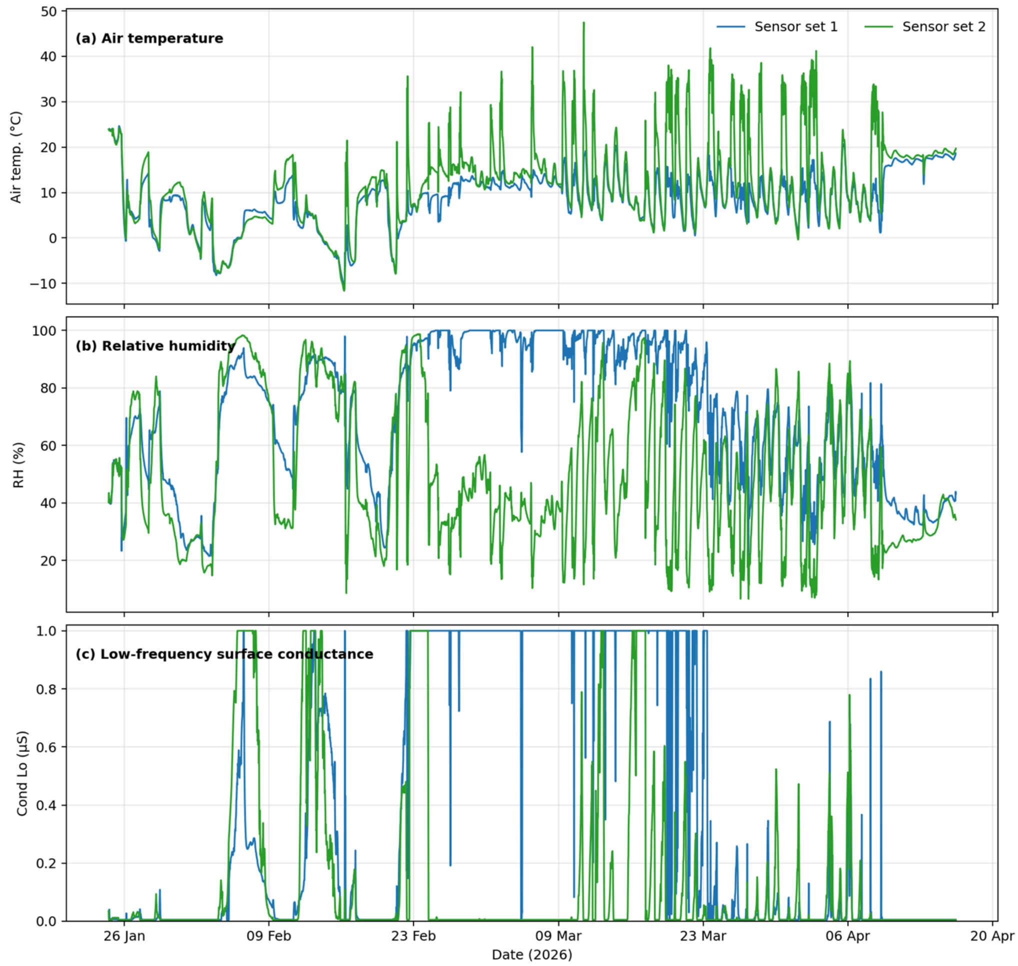

Figure 2. Full-campaign signals for Sensor set 1 and Sensor set 2: (**a**) air temperature, (**b**) relative humidity, and (**c**) low-frequency surface conductance. Continuous operation for ~82 days, with repeated returns to the dry-state baseline, demonstrates that autonomous deployment was feasible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

The signal-continuity metrics and final corrosion totals for both sensor sets are summarized in Table 2.

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

3.2. Representative In-Service Signals

The two sensor sets captured two distinct classes of in-service response (Figure 3). Sensor set 2 showed a condensation-driven activation sequence. Between 5 and 14 February 2026, RH rose 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 reflects the gradual build-up of a persistent electrolyte film on the horizontal surface below the gearbox.

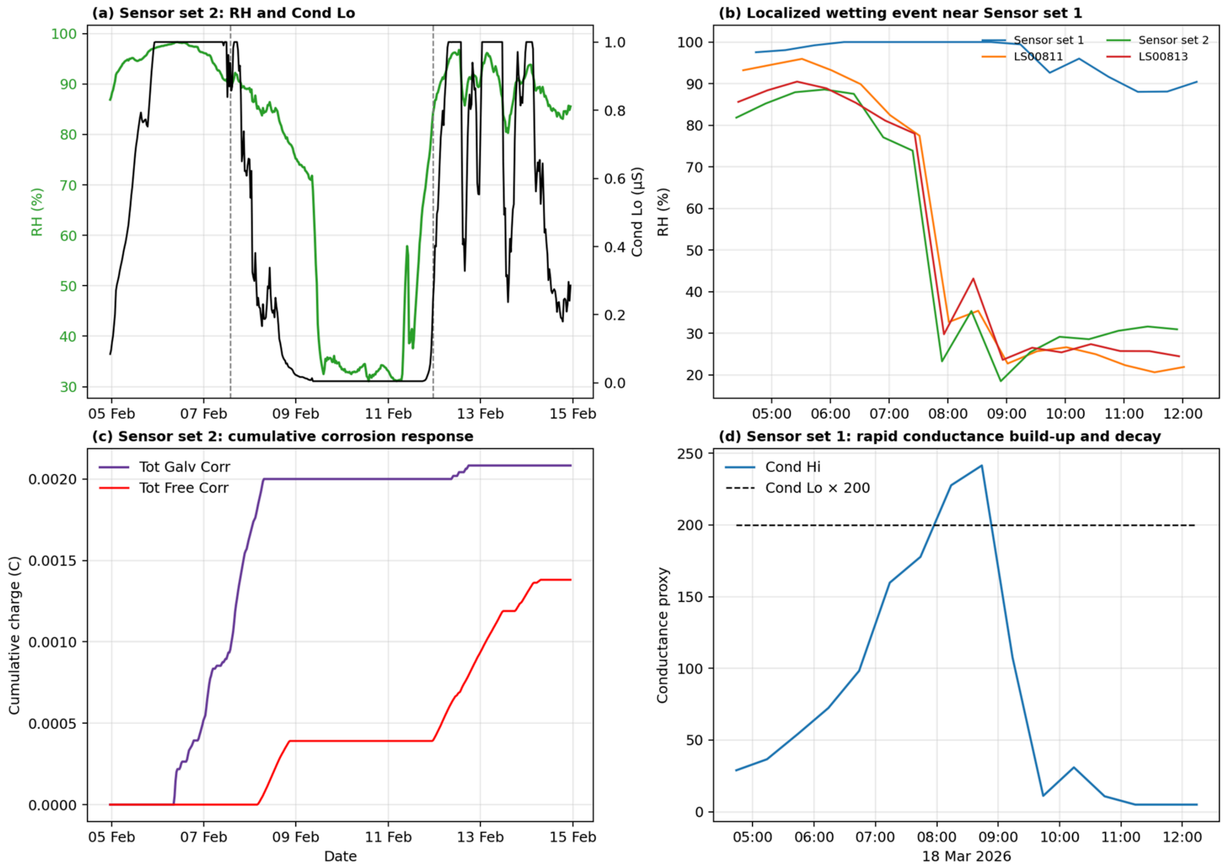

Figure 3. Representative in-service signals. (**a**,**c**) Sensor set 2 during the February condensation-driven activation sequence, showing RH and Cond Lo build-up followed by galvanic and free-corrosion accumulation. (**b**,**d**) A localized wetting event occurred near Sensor set 1 on 18 March 2026,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

Sensor set 1 showed a far more persistent underfloor wetting signature. Over the full campaign, it reached Tot Free Corr = 0.007995 C—well above Sensor set 2 (0.001381 C)—while its galvanic total was comparable (0.002231 C vs. 0.002103 C). The dominant free-corrosion episode (22 February 12:09 to 24 February 10:39, 47 h) contributed 0.002710 C—33.9% of the final free-corrosion charge. The dominant galvanic episode (27 February 14:39 to 28 February 08:39, 18.5 h) contributed 0.000907 C—40.7% of the final galvanic charge.

A notable event on 18 March 2026 illustrates the underfloor trapping mechanism. 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. The signal shape is more consistent with localized liquid ingress or trapping beneath the floor than with ambient humidity alone. Accidental spillage or leakage of transported fluids is a plausible cause, but the present sensor set does not identify the fluid chemistry directly.

The dominant corrosion-related charge-accumulation episodes are summarized in Table 3.

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	7 February 14:50–8 February 08:20	18 h	0.001066 C	50.7%
Sensor set 2	Free	12 February 00:20–13 February 12:50	37 h	0.000798 C	57.8%
Sensor set 1	Free	22 February 12:09–24 February 10:39	47 h	0.002710 C	33.9%
Sensor set 1	Galvanic	27 February 14:39–28 February 08:39	18.5 h	0.000907 C	40.7%

3.3. Corrosion-Prone Condition Indicator

The RH–conductance space offers a practical way to distinguish merely humid conditions from truly corrosion-prone conditions (Figure 4). Sensor set 2 is useful for identifying onset behavior because it experienced the full dry-to-wet-to-corrosive transition without the pronounced underfloor liquid trapping seen on Sensor set 1. For persistent episodes of 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. Conductance, rather than RH alone, is the more direct indicator of an electrochemically active electrolyte film.

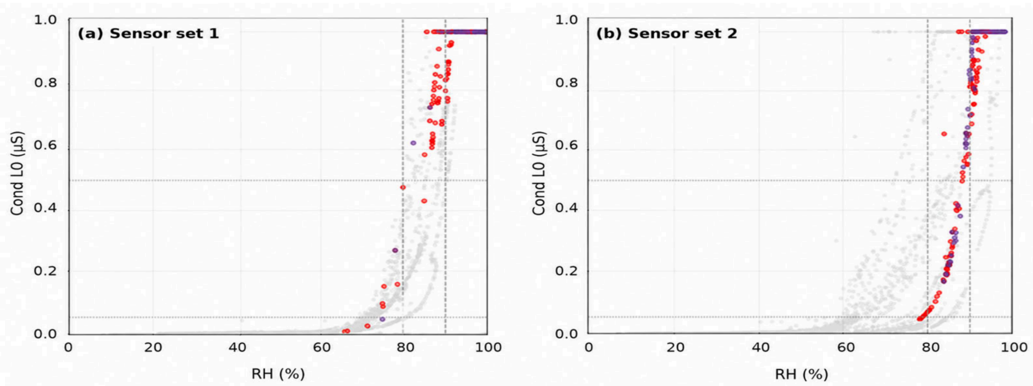

Figure 4. Empirical activation maps in RH–conductance space. Gray points indicate no increment in cumulative corrosion charge; red points indicate free-corrosion increments; purple points indicate galvanic-corrosion increments. Dashed lines show RH = 80% and 90%; dotted lines show Cond Lo = 0.05 and 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.

A conservative corrosion-prone condition indicator (CPCI) was defined as RH $\geq$ 80% and Cond Lo $\geq$ 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. These results confirm the indicator's sensitivity for the present data set, but should not be read as universal statistical limits. The 82-day campaign covered only the initial operational period and did not include full seasonal, mission-profile, or geographic variability. CPCI is a screening indicator—its purpose is to identify conditions that, if sustained, may promote future corrosion initiation—not a quantitative damage metric. For other aircraft, installation positions, climates, or mission profiles, the physical logic applies, but numerical thresholds and persistence windows should be recalibrated using local baseline data and, where available, inspection or NDT feedback.

A stronger regime (RH $\geq$ 90% and Cond Lo $\geq$ 0.5 µS) corresponded to 133.5 h in Sensor set 2 and 627.0 h in Sensor set 1. This higher threshold captures the most severe and long-lasting wet states, especially in the closed underfloor volume, and provides a practical escalation level for maintenance-oriented warning assessment. Its significance is prospective: it marks persistent exposure severity that may justify preventive intervention and activation of higher-level diagnostic layers, but does not by itself prove that structural corrosion damage is present.

3.4. Warning-Level Assessment for Closed Zones

For closed or difficult-to-inspect aircraft zones, the data support a three-level warning logic: Watch = RH–conductance framework: Watch = RH $\geq$ 80% and Cond Lo $\geq$ 0.05 µS; Warning = RH $\geq$ 90% and Cond Lo $\geq$ 0.5 µS; Severe = RH $\geq$ 95%, Cond Lo = 1.0 µS, and Cond Hi $\geq$ 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. Each state is prospective, not confirmatory: it indicates that the monitored zone has experienced persistently unfavorable conditions warranting increased surveillance, preventive action, or higher-level diagnostics—not that corrosion damage is already present.

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.

The key observation for maintenance is that persistence matters more than peak amplitude in closed zones. Short excursions were separated from persistent episodes using the duration rules from Section 2.6; warning and severe episodes longer than 6 h were counted separately as maintenance-relevant events. When the severe state persists for several hours, inspection should cover not only corrosion products but also drainage paths, local ventilation, and fluid-ingress routes. In the proposed architecture, such states would justify PZT-based localization and local eddy-current or NDT verification when access permits. The operational note that abrupt Sensor set 1 excursions occurred during flight missions further supports inspecting for underfloor liquid ingress or spillage after severe alarms.

Sensor set 2 is best suited for deriving the empirical corrosion-onset envelope; Sensor set 1 is the more relevant sensor for warning-level assessment in closed aircraft zones. Together, the two signals show that CHM sensors can distinguish between broad humidity-driven corrosion risk and the more critical local wetting events that require direct maintenance action.

When interpreted through the proposed maintenance-support 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 underfloor compartment. From the maintenance crew's perspective, the system's significance lies not in autonomous AI decision-making, but in presenting a traceable graded alert that shows which thresholds were exceeded, for how long, and which predefined maintenance action is recommended, as summarized in Table 1.

The data also illustrate the practical role of sensitivity settings. A lower-sensitivity configuration escalates only the longest and most persistent events—useful when nuisance alerts must be minimized. A higher-sensitivity configuration flags shorter but repeated wetting episodes earlier, which may be preferred for older aircraft, after contamination events, or in zones that are difficult to inspect. This tunability is important for integrating the warning logic into an operational maintenance information system [8,12–15].

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

The campaign focused on environmental, conductance, and electrochemical channels because the system had only recently entered operation. The severe and long-duration events identified for Sensor set 1 define the most relevant time windows and structural zones for future higher-level follow-up diagnostics. No PZT or eddy-current sensors were installed on the flying helicopter during this initial campaign—not as a methodological omission, but because installing additional sensors on a real aircraft requires maintenance access, aircraft downtime, integration with service procedures, and an operational justification. Although severe early-warning episodes were detected, they did not coincide with an approved maintenance-access window or dedicated flight-test opportunity during this initial period.

In this staged framework, PZT sensing is intended to localize subregions where corrosion-related degradation may have initiated—not to identify corrosion chemistry, but to detect where the local structural response deviates from the baseline. This layer has been validated separately. 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 [17]. Later work showed that PZT-network decision logic should be corrected for environmental and operational variability, since temperature-driven drift increases the false-call rate without correction [21]. These results support the readiness of PZT-based SHM networks for future aircraft follow-up tests, but the present field campaign does not yet include PZT localization data from the monitored helicopter [17,21].

Eddy-current sensing constitutes the subsequent verification and progression-monitoring layer. After a suspect subregion has been identified, EC sensing can confirm whether local metallic degradation is present and can monitor its growth over time. Multifrequency, aircraft-oriented eddy-current inspection has been shown in controlled studies to improve crack visibility and support the assessment of size, depth, and location in multilayer airframe structures [22]. Other studies have demonstrated electromagnetic testing combined with machine learning for hidden aircraft corrosion detection and automated eddy-current-capable inspection platforms for practical aviation NDT deployment [18,23]. In the context of the underfloor 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. Importantly, direct quantification of pit depth, mass loss, crack initiation, or local damage growth would become possible only after this local EC/NDT layer is installed or after targeted physical inspection is performed. The currently installed sensors should therefore be understood as environmental and electrochemical warning devices, not as direct corrosion-damage metrology.

https://doi.org/10.3390/app16125807

4. Discussion

4.1. Relevance for SHM and Condition-Informed Maintenance

The proposed multi-sensor approach extends SHM beyond structural response to include the environmental and electrochemical conditions that promote corrosion in enclosed aircraft zones. This is especially relevant in underfloor spaces, where direct inspection is limited and corrosion can develop unnoticed between maintenance actions. Combining humidity, temperature, surface conductance, and corrosion-related signals gives a more realistic representation of the monitored zone's condition than any single-parameter observation [2].

The main practical advantage is earlier identification of conditions that may lead to hidden corrosion, allowing action before corrosion progresses to damage requiring repair. Monitoring output informs decisions about whether the compartment should be opened, cleaned, inspected, or checked for drainage issues or fluid ingress—preventive action against corrosion-promoting conditions rather than corrective action after damage has occurred [2,16].

A practical consequence is that closed zones need not be opened solely because a fixed maintenance interval has been reached. Opening and cleaning can be prioritized when the measured local environment indicates persistent wetness or electrochemical activity. This is condition-informed maintenance support, not a complete prognostic CBM solution. The system does not yet estimate remaining useful life or predict corrosion-growth kinetics; it identifies periods and locations where the probability of corrosion initiation is elevated and inspection is better justified.

The method is not limited to aerospace structures. The same early-warning, localization, and follow-up logic can be transferred to civil engineering components with hidden or difficult-to-access zones—closed steel details, box sections, joints, anchorages, cavities—where moisture retention and delayed inspection allow degradation to develop unnoticed. The helicopter application is a demanding real-world demonstrator of a general SHM methodology based on persistence analysis and staged diagnostic escalation.

4.2. Traceable Maintenance-Support Interface and Transition Toward CBM

A key practical extension is integrating fused sensor interpretation with a traceable maintenance-support interface. The system first classifies warning states using deterministic thresholds and persistence rules. The GPT-type module then prepares a human-readable alert that explains the event, lists the exceeded criteria, and links the warning level to a predefined maintenance recommendation. This separation is important for aviation use: the diagnostic classification must remain reproducible from sensor data and the rule base, while natural-language generation serves only to improve communication with maintenance personnel.

This logic supports a gradual transition from fixed-interval inspection toward condition-informed maintenance and, in the longer term, condition-based maintenance. At the present stage, however, the system is not a full CBM or prognostic solution. It does not estimate remaining useful life, model corrosion-growth kinetics, or autonomously optimize intervention timing. Its demonstrated value is narrower but operationally useful: it provides early evidence that a hidden zone has experienced persistent corrosion-promoting conditions and helps maintenance personnel decide whether continued observation, ventilation, drying, cleaning, opening, or targeted NDT is warranted.

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.

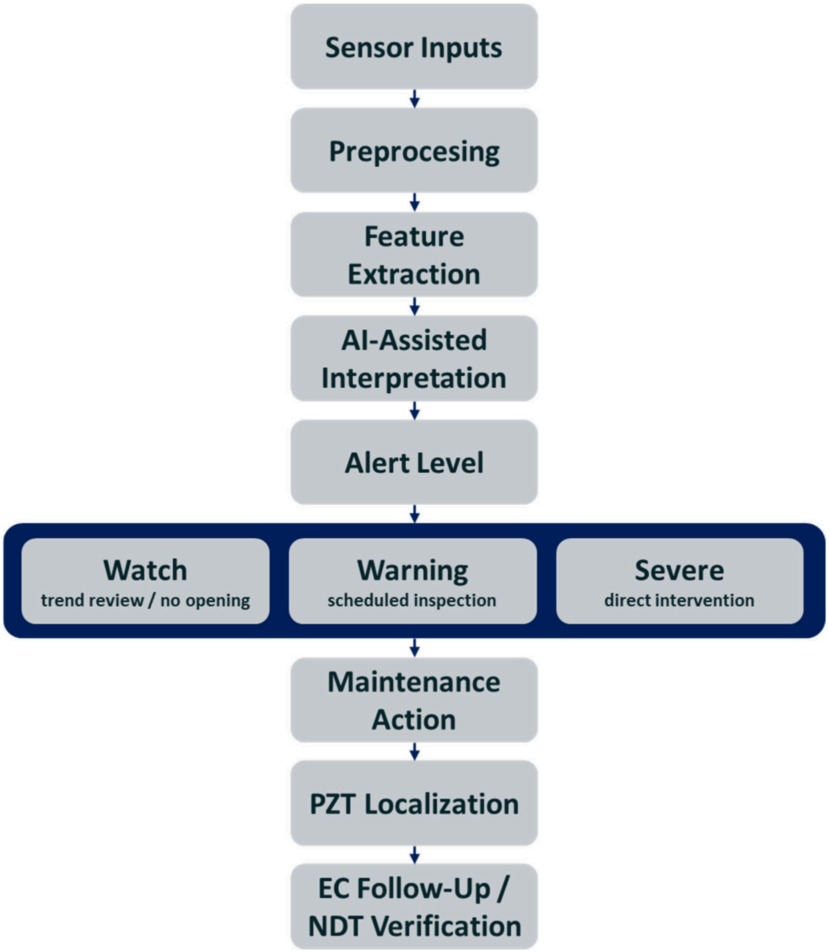

Figure 5. Block diagram of the proposed traceable multi-sensor corrosion-warning and maintenance-support architecture for closed helicopter zones. Sensor inputs are first preprocessed and then interpreted using threshold- and persistence-based data fusion. The GPT-type module is limited to natural-language reporting of the predefined alert class and maintenance recommendation. PZT and eddy-current sensors are shown as planned follow-up diagnostic layers rather than as field-validated outputs of the present 82-day campaign.

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 a traceable rule-based layer that recognizes abrupt increases in humidity, persistent surface wetness, conductance excursions, and 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 a future operational extension, PZT sensing would support localization of the most suspect structural subregion, whereas eddy-current sensing and targeted NDT would 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 a replacement for non-destructive testing. Its role is to support targeted NDT by identifying where and when detailed inspection is warranted. In hidden aircraft zones, this is especially useful because direct access often requires panel removal and other labor-intensive steps. The monitoring system serves as an early screening layer that helps prioritize compartments with elevated corrosion risk [18,23,29].

Inspection efficiency may improve in two ways. If the monitored zone remains low risk, unnecessary structural opening can be deferred. If warning or severe conditions are recorded, the information directs NDT to the most relevant location and time window. Environmental and electrochemical signals define the general condition of the monitored zone but do not identify damage type or location directly. PZT sensing localizes the most suspect subregion after a persistent warning state; eddy-current sensing provides local confirmation and follow-up monitoring of degradation growth at a specific metallic detail, such as a joint between a composite panel and the aluminum helicopter structure [17,18,21–23,29].

These sensing layers are complementary tools. Final confirmation of damage and maintenance decisions still require appropriate inspection methods, NDT procedures, and engineering assessment. The main contribution of the proposed system is better-targeted NDT and maintenance actions, not the elimination of inspection [18,23,29].

4.4. Limitations and Practical Implementation Issues

First, the CPCI and the associated Watch/Warning/Severe thresholds are not direct measures of corrosion damage. They are early-warning criteria designed to flag conditions that, if sustained, may promote corrosion initiation and growth. Derived from an 82-day initial campaign and two sensor sets, they should be treated as empirical screening values rather than universal statistical limits. Assessing threshold drift and recalibrating the warning logic for other aircraft types, structural details, climates, and service environments will require additional seasonal data, different mission profiles, and additional installation sites. The same applies to potential civil engineering use: the methodology transfers conceptually, but threshold calibration must be performed for the specific material system, exposure scenario, and inspection strategy of the target structure.

Second, the current sensor layout should not be interpreted as proof of complete spatial coverage of all high-risk closed zones. The two focus sensor sets were installed in priority locations selected from engineering judgment and expected liquid-retention paths, but corrosion risk in enclosed aircraft compartments is spatially heterogeneous. Unmonitored blind spots may remain, especially near drains, penetrations, lap joints, fasteners, seal discontinuities, and local debris or contaminant traps. A mature fleet implementation should therefore combine the present warning logic with a risk-based sensor-placement map, additional measurement points where justified, and periodic feedback from inspection findings.

Third, interpreting the sensor response depends on the operational context. Understanding severe underfloor events may require additional information—mission history, weather conditions, cleaning records, and possible contamination by operational fluids. The current sensor set distinguishes dry, humid, conductive, and electrochemically active states, but cannot identify whether the electrolyte originated from condensation, water ingress, blood, saline, disinfectant, or other mission-related fluids. Such fluids can alter conductance and electrochemical response, and may therefore influence warning frequency. Future implementations should consider additional source-tracking information or supplementary sensors such as pH, chloride, ion-selective, flexible iontronic, or thin-film wetness elements where operationally feasible [24–28].

Fourth, the present in-service validation covers the early-warning layer based on environmental, conductance, and electrochemical sensing. PZT and eddy-current sensing are defined here as staged follow-up diagnostics: PZT sensing localizes probable corrosion-affected subregions, and eddy-current sensing confirms and monitors local damage progression. Both layers have been validated separately in laboratory or controlled studies but were not installed on the flying helicopter during this initial period. Installing additional sensors on a real aircraft depends on aircraft availability, access to the monitored compartment, maintenance planning, approval of the installation procedure, and a justified operational trigger. Persistent severe early-warning episodes were observed during the campaign, but none coincided with an approved maintenance or flight-test window suitable for PZT and EC installation. Their full integration into the operational workflow remains a planned next step.

In operational aircraft, 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 for validation purposes alone. The present work should therefore be treated as a first in-service validation stage: the early-warning thresholds are supported by in-service measurements and by field evidence showing that prolonged corrosion-prone conditions in hidden zones can eventually lead to costly corrosion damage [1,2]. Correlating warning episodes with pit depth, mass loss, crack initiation, or local damage-growth rate will require targeted inspection and installation of the EC/NDT follow-up layer. Further validation should progressively link warning episodes with direct inspections, PZT-based localization, eddy-current follow-up, and maintenance findings. The same limitation applies to civil engineering assets with hidden zones, where repeated intrusive opening for one-to-one validation may be technically possible but economically unjustified.

Fifth, the economic benefit of the proposed system was not quantified in this study. The expected operational value lies in reducing unnecessary floor-panel removal, shortening troubleshooting time after wetting or contamination events, and preventing late discovery of extensive hidden corrosion. A rigorous cost–benefit assessment requires longer fleet use, records of actual maintenance decisions, labor hours, aircraft downtime, installation costs, sensor replacement costs, and corrosion-repair costs—data not yet available because the system had only recently entered service. Future work should compare the warning-supported workflow with conventional scheduled access and with simpler single-sensor strategies, using indicators such as avoided disassembly hours, false-alarm rate, confirmed findings, and repair-cost reduction.

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

Field inspection evidence supports the maintenance relevance of the proposed warning logic. Figure 6 shows examples of corrosion observed in a hidden aircraft zone after prolonged exposure to moisture-retaining and corrosion-prone conditions, identified in riveted and lap-joint-type details representative of the closed structural locations considered in this monitoring concept.

These findings support the practical interpretation of the adopted warning thresholds, but should not be read as a one-to-one temporal and spatial validation of specific Sensor set 1 or Sensor set 2 severe events. The photographs provide qualitative maintenance context: persistent corrosive conditions, even when detected only through environmental, conductance, and electrochemical indicators, can evolve into actual corrosion damage requiring costly corrective maintenance [1,2]. Corrosion removal and repair in the observed case were labor-intensive—requiring access to a closed zone, removal of corrosion products, cleaning, restoration of protective layers, and local repair. This justifies the early-warning approach and the need for staged follow-up diagnostics; direct localization and damage quantification require PZT, eddy-current sensing, targeted NDT, or physical inspection in future campaigns.

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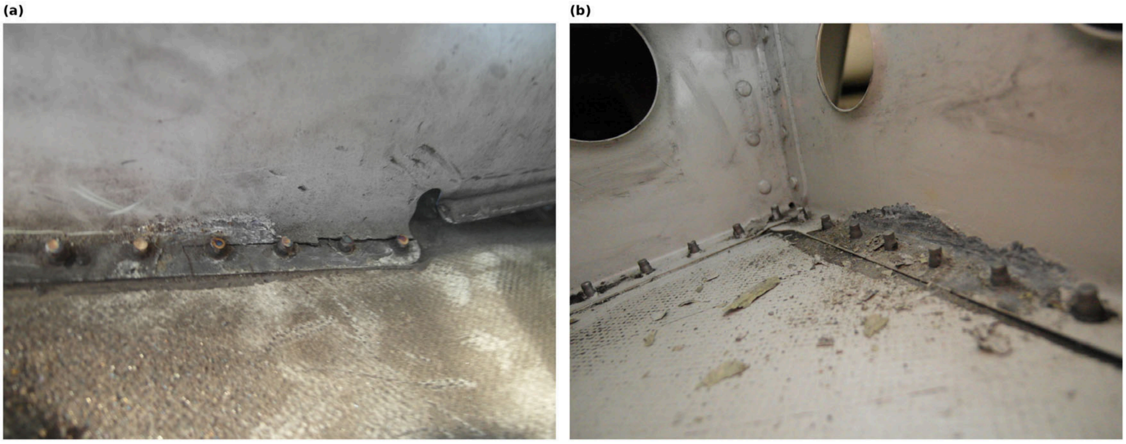

Figure 6. Field inspection evidence of corrosion in a hidden aircraft zone after prolonged persistence of corrosion-prone conditions. (**a**) Close-up view of corrosion damage developing along a riveted and lap-joint-type detail. (**b**) Wider view of corrosion products and degradation in a hidden structural zone. These photographs provide qualitative maintenance context for the proposed early-warning logic. They do not establish a direct one-to-one temporal or spatial correlation with the specific severe events recorded by Sensor sets 1 and 2 during the present campaign; rather, they show why persistent corrosion-prone conditions in closed zones should be treated as operationally important and followed, when justified, by localization and direct NDT/EC verification.

4.6. Outlook: Advanced Sensors and Computational Data Fusion

The next step is combining longer operational data collection with direct inspection feedback and higher-level diagnostic layers. In the near term, this means installing PZT and eddy-current sensors at the next approved maintenance window or dedicated aircraft-access opportunity. In parallel, the alert thresholds should be recalibrated using seasonal data, different mission types, and additional aircraft locations—allowing sensitivity, false-alarm behavior, and threshold drift to be quantified rather than inferred from a single 82-day campaign.

Longer-term research should explore advanced sensing and computational augmentation. Flexible iontronic, ion-selective, and conformable multimodal sensors could add pH, chloride, thin-film wetness, or liquid-composition information to the present warning layer [24–28], helping to distinguish condensation from mission-related fluids and reduce ambiguity in severe events. Physics-informed or simulation-assisted machine-learning models could generate virtual corrosion-prone scenarios under coupled temperature, humidity, electrolyte, and electrochemical conditions [19,20]. These techniques are presented here as an outlook because they require training and validation data, and aviation traceability, that are not yet available from the initial field campaign.

5. Conclusions

This paper reports an in-service validation of the first monitoring layer of a multi-sensor data fusion approach for early warning of corrosion-prone conditions in closed aircraft zones. Environmental, conductance, and electrochemical sensing identified persistent unfavorable conditions in hidden compartments during aircraft operations and distinguished general humidity exposure from more critical long-duration wetting events. Within the proposed architecture, these first-stage signals indicate increased long-term corrosion risk; they do not constitute direct proof of existing structural damage.

From a maintenance perspective, the approach supports condition-informed decision-making in areas where routine inspection is difficult. The installed sensors characterize the general environmental and electrochemical conditions of the monitored zone and indicate whether corrosion-favorable conditions have persisted. They do not determine corrosion type, exact location, pit depth, mass loss, or crack initiation. Their outputs should inform decisions about whether a closed zone should be monitored further, aired, dried, opened, cleaned, or inspected—not serve as substitutes for NDT or engineering assessment.

Complete case-by-case validation in operational aircraft is inherently limited by access, cost, availability, and airworthiness constraints. The present study is the first operational validation stage toward a fully integrated corrosion-warning and follow-up monitoring framework. Further maintenance opportunities are required before the PZT and eddy-current follow-up layers can be installed and validated on the flying helicopter.

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. PZT and eddy-current sensing remain important follow-up layers, validated separately in laboratory or controlled conditions and ready for aircraft implementation when a persistent warning state or scheduled access opportunity justifies installation. The same logic may be adapted to civil engineering structures and infrastructures with hidden or difficult-to-inspect zones, but sensor selection, thresholds, persistence criteria, and maintenance actions must be recalibrated for the relevant material system and exposure environment.

The proposed solution shifts maintenance from reacting to already developed corrosion damage toward acting on persistent corrosion-promoting conditions. Future work should address seasonal validation of the CPCI thresholds, direct correlation between warning states and inspection findings, aircraft installation of the PZT and eddy-current follow-up layers, evaluation of pH/chloride or other liquid-composition sensing for source tracking, exploration of flexible iontronic and conformable multimodal sensors, physics-informed virtual scenario generation, and quantitative assessment of maintenance benefits including reduced unnecessary access, reduced disassembly labor, and earlier targeting of corrective action [8,12–15,19,20,24–28].

Author Contributions: Conceptualization, P.C.; methodology, P.C., L.V.-G., A.K. and M.D.; investigation, P.C., L.V.-G., L.M., A.B. and A.N.; validation, P.C., L.V.-G., A.K., M.D., L.M., A.B. and A.N.; formal analysis, P.C., M.D. and A.B.; data curation, P.C., L.V.-G. and A.N.; writing—original draft preparation, P.C.; writing—review and editing, L.V.-G., A.K., M.D., L.M., A.B., A.N. and A.L.; visualization, P.C. and A.B.; supervision, M.D., A.K. and A.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the statutory work no. 31-1188-1 of the Air Force Institute of Technology (ITWL). The research was also partially supported by Polish National Center for Research and Development within the scope of the project LIDER13/0132/2022. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available from the corresponding author upon reasonable request. The authors agree to provide the research data for scientific and editorial verification.

Acknowledgments: During the preparation of this manuscript, the authors used a GPT-5.1-based generative AI tool for translation support and for adapting the text between the working manuscript and the Applied Sciences journal template. The authors reviewed and edited the output and take full responsibility for the content of this publication. M.D. would like to acknowledge support from the Polish National Center for Research and Development within the scope of the project LIDER13/0132/2022.

Conflicts of Interest: The authors declare no conflicts of interest.

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