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Digital Twin Concept Definition for Predictive Maintenance

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1 INTRODUCTION

This document defines the concept for predictive maintenance and how the AVATAR project intends to solve the challenges posed by the project brief. The goal of this report is to provide a roadmap for the development of the Digital Twin Platform and the associated development and use of technology required to obtain the goals of the AVATAR project. The definition of the term Digital Twin is elaborated and the high-level requirements in order to meet the project goals are defined.

1.1 THE AVATAR PROJECT

The AVATAR title is an acronym created for a project with the full title “Transformative Digital Air Vehicle with IoT Sensors for Safer Urban Skies” created to the call HORIZON-CL5-2022-D5-01. The project summary states:

“AVATAR is dedicated to developing a digital twin platform to enable continuous monitoring of the vehicle during its service life for the purpose predictive maintenance. AVATAR’s digital twin model acts in parallel to the real structure and provides, where necessary, an early warning of operational behaviour that deviates from expected (simulated). Additionally, by recording the actual load spectrum that each air vehicle experiences during every flight, it will optimize the individual service life, which contributes towards a sustainable air mobility. AVATAR’s will contribute to an increase safety of urban skies and has the potential to optimise the design and performance of air vehicles by providing real load data for each vehicle. The IoT sensing skin proposed by AVATAR is a key enabler for real-time critical operational information acquisition and connectivity between the physical aircraft and the digital counterpart through wireless communication. AVATAR DT platform will provide a seamless integration of IoT, big data and machine learning to collect, compute and predict. AVATAR will conform to the modern approach towards developing a digital twin based on different types of data and advanced analytical methods which eliminates the need for the real air vehicle and the virtual models to be directly connected and builds this connection through ML and AI. AVATAR contributes to the acceleration of digital transformation of air mobility, particularly in urban setting.”

1.2 GOAL OF THIS REPORT

This deliverable provides the roadmap for the development of AVATAR’s DT platform, setting the requirements for the technological and computational developments. To achieve this objective, the functional and computational requirements of the system are defined first. Key aspects of the deliverable include:

- Define (manned and unmanned demonstrators) existing design concepts and service life.
- Select appropriate prognostic models for predicting the remaining useful life.
- Define the assessment criteria for the PdM platform.
- Identify historical load profiles for demonstrator aircraft to serve as a prior distribution to be input for probabilistic prognosis in WP4 and WP5.
- Identify possible suitable sensor positions to be used in WP2, WP4 and WP5.
- Define criteria of accessibility of individual sensors during regular checks, of their repairability and of a potential of damaging events or of aggressive environment affecting their function or performance.

2 THE DIGITAL TWIN CONCEPT

The purpose of the Digital Twin (DT) Concept is in essence to create a real-time monitoring framework to continuously assess the physical health of the target airframe with the aspect of being able to plan maintenance and determine the remaining useful life of that airframe.

AVATAR's concept for health management of air vehicles is illustrated in Figure 1.

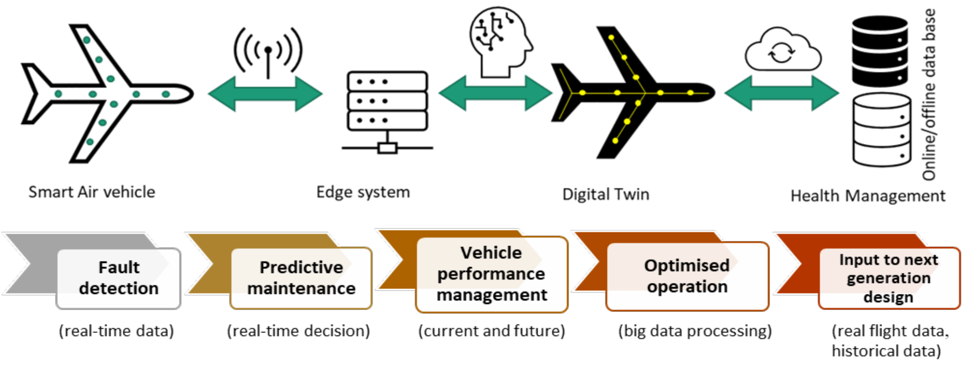

Figure 1 Continuous in-situ and distributed monitoring of air vehicles' structural integrity

The Digital Twin (**DT**) concept is deemed it could revolutionize the industry by providing a tight and real-time relation (twinning) between the simulation and physical reality. Virtual modelling until recently focused on creating theoretical virtual models, the boundary conditions for analysis of which related more to expected inputs or design restraints than to reality.

2.1 THE PREDICTIVE MAINTENANCE PROCESS

To discuss the topic of Digital Twin Concept, the concept of Predictive Maintenance needs to be defined and elaborated in the context of the project.

The development of a new predictive maintenance (PdM) approaches favours data-centric maintenance strategies for both metallic and composite aircraft structures in order to maximize the efficiency by predicting when maintenance is required. This will reduce operational costs by preventing unplanned downtime and extending the component's lifespan. Within the AVATAR project, this aims to achieve it through the Digital Twin concept merged with data from Structural health Monitoring.

. The core concept of predictive maintenance involves the following:

- **Data Acquisition**: Continuous monitoring and collection of data from sensors placed in strategic locations on and in the aircraft structure. This data includes temperature, strain, and accelerations.
- **Data Analysis**: Advanced analytics, including machine learning and statistical methods, are applied to the collected data to identify patterns, anomalies, and trends that may indicate potential parts failures or maintenance needs, as a supplement to data generated in the design phase of the aircraft.
- **Condition Monitoring**: The real-time assessment of equipment condition is a critical aspect of PdM. By continuously monitoring structures conditions, the Digital Twin can detect deviations from normal operating parameters and design criteria.

Sensitivity Label: General

- **Predictive Models**: Predictive maintenance relies on the development of predictive models that use historical data, design data where possible (iaw ~ initial airworthiness standards) and current conditions to forecast when structure is likely to fail or require maintenance. These models may include techniques such as regression analysis, time-series forecasting, and neural networks.
- **Maintenance Alerts**: When the predictive models identify a potential issue or maintenance requirement, alerts are generated. These alerts can be based on predefined thresholds or statistical deviations from normal behaviour predictions.
- **Scheduled Maintenance**: Maintenance activities are scheduled, planned, and performed based on the predictions and alerts, while the use of PdM helps to reduce it significantly.
- **Data Integration**: PdM often involves the integration of various data sources, including sensor data, maintenance history, initial airworthiness data and operational data, into a centralized system or platform for comprehensive analysis and decision-making.

In summary, predictive maintenance under the AVATAR project enables a proactive maintenance strategy that leverages data analytics and predictive models to anticipate failures of critical parts. By adopting PdM, the aeronautical industry can move away from a conservative scheduled maintenance approach and achieve improved reliability, reduced downtime, and cost savings.

2.2 THE DIGITAL TWIN PROCESS

The DT concept is based on physical input from a physical structure. Because this input differs from structure to structure, or due to varying in-service environmental conditions, the twinning process becomes adaptive and closer related to the structure, which is monitored.

For a specific structure monitored throughout its entire in-service life, it allows, at any time, to estimate the remaining service life. Only generalization over a larger fleet of such monitored structures could allow the analysts to derive more general outputs to be applied e.g., as design rules for further development.

Successfully implementing this evaluation process into the aviation industry should help to reduce the danger related to the usage of fixed-wing UAVs (unmanned aerial vehicles) over urban areas, when each such unit could be monitored and real-time evaluated for endangering events or any structural deficiencies developed gradually during the service. Its usage should help also in the general and commercial aviation, or in the domain of ultralight airplanes, where currently very little demands are requested. It should be noted here however, that AVATAR’s TRL is within 2-4. It focuses on showing implementation of DT is feasible, and which type of output it can provide, so that the certification bodies may assess the viability of such a concept, and the potential changes it can result in. To be clear, the AVATAR project does not aim to deliver a certifiable package compliant with applicable Certification Specifications and/or MSG3 packages.

To implement the concept in close future, some key issues separated in different AVATAR’s WPs must be solved:

- Developing appropriate sensor units, which, e.g., for the UAV application shall be of small dimensions and with minimum weight due to size and weight constraints.
- Within the same size and weight constraints, to develop the data processing units and data transmission units required to gather and transmit data.
- Managing the adequate data processing procedures to clean the data and minimizing the necessary content to be sent from the air vehicle.
- Data transmission protocols in order not to affect the avionics of the aircraft or other potentially harmed systems.

- To further store / process / categorize the retrieved large scope data on ground to prepare them for the fatigue life analysis.
- Developing surrogate models to replace the time demanding finite element analyses by computationally more efficient models for each evaluated critical locality; including the implementation of AI-driven analyses.

3 DESIGN CONCEPTS

The design concepts and assessment criteria related to the demonstrator aircraft are within the scope of either safe-life or damage tolerance analysis. For the two concepts, the input, processing routines and outputs are defined at a high level, in order to provide a framework for the structural health-monitoring solutions to be developed.

3.1 SAFE-LIFE ANALYSIS

AVATAR's focus lies on the development of structural health-monitoring solutions, which indicates a forward-looking approach to enhancing safety and reliability in aircraft operation. This suggests an interest in leveraging technology to improve the monitoring and maintenance of aircraft structures, potentially leading to increased operational efficiency and safety. Safe-Life design in aeronautics refers to a design philosophy and approach that focuses on ensuring the structural integrity and safety of an aircraft or its component for a specified service life, typically through a predetermined number of flight hours or cycles. The concept assumes that any crack should not develop within the critical components of the aircraft.

Safe-Life design begins with an understanding of the materials used in the aircraft's structure and the expected loads and stresses it will encounter during its service life. Fatigue analysis is performed to predict how these materials will degrade over time due to repeated loading and unloading cycles. Based on fatigue analysis and material properties, a specific service life or "life limit" is established for critical components, with a pre-determined safety margin. This limit is often expressed in terms of flight hours, cycles, calendar time, and/or operating conditions. Safe-Life components must undergo regular inspections to detect signs of fatigue or damage. These inspections are an additional safety measure, and they help ensuring that the component remains safe for its intended service life. If any damage or wear exceeds specified limits, the component may need repair or replacement. Safe-Life design also specifies criteria for component replacement when they reach the end of their predetermined service life or if they exhibit excessive wear or damage that cannot be safely repaired. Aircraft are often equipped with data recording systems that monitor the number of flight hours and cycles, as well as other relevant parameters. This data is crucial for tracking the service life of various components.

3.1.1 INPUTS

The inputs for the Safe-Life Analysis are historically given in the pre-determined load cases for each individually certified aircraft. The load cases are defined for each structural part of the aircraft, ensuring that the aircraft is designed to withstand the life-span. The design inputs for the Safe-Life analysis are calculated conservatively with a safety margin in order to allow for a statistical span of load spectres to be endured during the operational life of the aircraft. This includes encountering heavy turbulence, hard landings, etc.

The other input for the computational routine related to the Safe-Life analysis is the knowledge about the load cases induced within individual load spectra, and the resulting stresses or strain on evaluated components obtained from finite element (FE) analysis. Usually, such analysis is assumed to be linear one, and the reference load cases to be analysed then are computed for loading related to 1g on air (flight mode) and on ground (taxi).

The last input for the fatigue analysis are the S-N curves (S for Stresses, N for Number of cycles) either of material or related to a specific structural detail (i.e., e.g., the specific joint, or some notched or riveted component). Based on the input stress values, the resulting fatigue life can be obtained from such a curve.

For Safe-Life design, proper testing is of the outmost importance, verifying that the actual design meets the loads experienced by complex metallic and composite structures during its operational life. Testing will also be important in order to validate the numerical models developed.

Taking into account the design data developed by the airframe manufacturer, the AVATAR project hopes to include such data in the modelling of the Digital Twin. This will allow for a more robust baseline of data, ensuring that validation of project goals is more in tune with useable requirements.

3.1.2 PROCESSING ROUTINES

Within the AVATAR project, the processing units shall be developed in accordance with applicable standards for aeronautical use. The loads deduced from the FE-analysis (FEA) for 1g load cases are scaled to achieve local loads which are repeated according to the number of occurrences provided by the specific load spectra. The obtained local or nominal stresses are then analysed with a specific fatigue S-N curve of material or of a component (including the specific notch factor corresponding to the critical hot-spot on the structure). The mean stress of each deduced load cycle should be involved in the analysis. For each load level and number of occurrences, the partial damage induced is computed. The total sum of all partial damages then sets the estimated mean fatigue life, which must be reduced taking into account the relevant safety factor requested usually by the certification body.

3.1.3 OUTPUTS

The safe fatigue life of the evaluated component is the output of the computational procedure. This is the maximum life the component can withstand in service and once approaching it, it has to be replaced by a new component, or the aircraft cannot be left in service.

Though the fatigue life estimation is deemed to be essentially conservative thanks to the high safety factors, the producer usually prescribes regular in-service checks to assure that some overloads, cases of misuse or other unknown factors could not reduce the service life of the aircraft. Once any substantial damage (a visible crack in the Safe-Life approach) is found on primary structures, the aircraft must be grounded until the issue is solved.

3.2 DAMAGE TOLERANCE APPROACH

In contrast to Safe-Life, the Damage Tolerant structure is designed to withstand predefined damage or flaws without resulting in catastrophic failure. Damage tolerance is an engineering approach that focuses on designing and analyzing aircraft structures and components to withstand and safely manage the growth of damage or cracks and defects, over their operational lifespan. Fracture mechanics principles are utilized to analyze the behaviour of materials and structures with existing flaws or cracks. This analysis determines the critical size of a flaw or crack that could lead to catastrophic failure under various loading conditions and mitigates the crack growth through tailored inspection programmes critical to the airworthiness of the aircraft. Computational tools and testing are essential to predict how cracks or damage may propagate over time and under different operational conditions. This information is critical for assessing the remaining structural life of a component. Aircraft components are regularly inspected using non-destructive inspection (NDI) techniques to detect and assess the size and severity of any flaws or cracks. These inspections help ensure that any damage is discovered, identified, managed, and mitigated before it reaches a critical size. Unlike Safe-Life design, Damage Tolerant design mitigate damage propagation by including procedures for repairing or addressing damage found during inspections.

Development of predictive maintenance is based on structural health monitoring (SHM) techniques. The basis of SHM is the application of permanently fixed sensors on the structure combined with the necessity of a minimum manual intervention to monitor the structural integrity. This enables a

continuous monitoring of the structure, and thus a detection of the defects at any stage of the predicted service life due to unforeseen events, to optimize the service life of each aircraft based on predictive maintenance (PdM). By applying a Digital Twin framework for predictive maintenance of air vehicles, in-flight loads, damage and operations can be recorded continuously, and the current and future states of the structure will be analysed in real time. Early warning and damage detection will be indicated as soon as possible to facilitate replacement or repair of the affected structures. The records of load and health states will be used dynamically to update the physical models and consequently the accuracy of the remaining useful life (**RUL**) prediction will improve resulting in a more sustainable transport mode, due to enhanced benefits as highlighted above. Therefore, continuous monitoring of the structure with SHM concept and model updating through a DT framework, has the potential to lower the uncertainty predicting the RUL of the structure. The real-time operational information of each air vehicle can be accessible through a front-end dashboard for real-time visualisation mapped against the CAD model of the structure. The novel real time data analytics engine for tracking air vehicles can be enabled by advanced analytical processing of large data from IoT sensors through edge/cloud computing.

3.2.1 INPUTS

The inputs for the Damage Tolerant approach are also historically given in the pre-determined load cases for each individually certified aircraft and coupled with the maintenance program and alternative load paths in order to detect damage and mitigate propagation via the alternative load carrying features until detection. The load cases are defined for each structural part of the aircraft, ensuring that the aircraft is designed to withstand the life-span loads predictive to be endured, coupled with the specific maintenance inspections. The design inputs for the Damage Tolerant approach are likewise calculated conservatively with a safety margin in order to allow for a statistical span of load spectres to be endured during the operational life of the aircraft. This includes encountering heavy turbulence, hard landings, etc. In addition, alternative load paths are defined in order to take into account structural damage. The maintenance program inspections are thus tailored to ensure that the damage propagation will not reach critical dimensions before discovered, thus mitigating the risk of catastrophic failure.

To develop alternative maintenance procedures, the comprehensive assessment for fail-safety and damage tolerance requires a multifaceted approach in acquiring essential input data. Within the SHM framework, PZT sensors play a pivotal role by providing detailed information regarding flaw location and size, contributing crucial insights into the structural integrity of the system under evaluation. Simultaneously, the integration of strain gauges and accelerometers enhances the assessment by furnishing data on fatigue loading, allowing for a thorough analysis of the stresses experienced by the components. Computational Finite Element (FE) models are also developed to compute the stress and strain resulting from known load cases. Usually, such analysis is assumed to be linear, and the reference load cases to be analysed then are computed for loading related to 1g on air (flight mode) and on ground (taxi).

The last input for the fatigue analysis are the S-N curves (S for Stresses, N for Number of cycles) either of material or related to a specific structural detail (i.e., the specific joint, or some notched or riveted component). Based on the input stress values, the resulting fatigue life can be obtained from such a curve. This also applies to structural elements included in the defined alternative load paths. Furthermore, the input parameters extend beyond sensor data to encompass essential information derived from physical models. Stress intensity factors, integral to understanding the potential for structural failure, are considered in the assessment. These factors, along with information from fatigue crack growth models and fracture toughness, are crucial components in evaluating the resilience of the system. Depending on their availability, these factors are obtained either from materials databases or through meticulous laboratory testing, ensuring a comprehensive and accurate analysis of the fail-safe and damage-tolerant characteristics of the system under scrutiny. This holistic approach not only considers the real-time sensor data but also incorporates fundamental material properties, thereby providing a robust foundation for the assessment.

3.2.2 PROCESSING ROUTINES

Taking defined Structural Significant Items (SSI) and Maintenance Significant Items (MSI) into account for calculations on the data model for reiteration of RUL will enable the DT to redefine the prognosis model for the service life of that given SSI/MSI. Using ML/AI in the definition of a reiteration of the RUL, will enable the design holder and the operator of a given aircraft to optimize usability of the aircraft, thus enhancing the value of the aircraft operation over time.

The processing routines for collected data shall be independent of existing aircraft systems, ensuring that there is no interference with certified installations. The independent system design shall take into account the possibility of future certification for either integration into the specific type design for the individual aircraft or as a supplemental type certification design for future implementation. The processing units developed for the project shall be developed in accordance with applicable standards for aeronautical use. Please note that the AVATAR project does not deliver a type-specific installation package certified for use.

3.2.3 OUTPUTS

To perform a fail-safe analysis, obtaining two critical sets of information is essential: residual strength and fatigue diagrams. These diagrams, integral to assessing structural integrity and remaining life, are derived through a process involving statistical analysis. This examination encompasses various factors such as load dynamics, fatigue parameters, and material data. Additionally, uncertainties linked to diagnostic information from sensor data are thoughtfully considered in the analysis.

To address and mitigate uncertainties related to acquired information, a statistical inference process is employed to formulate the Equivalent Initial Flaw Size Distribution (EIFSD). This method considers the inherent variability and potential inaccuracies in load, fatigue, and material data, as well as uncertainties associated with diagnostic information from sensor data. By incorporating the EIFSD, the analysis gains a robust framework that recognizes and accommodates the complexity of real-world conditions.

In summary, the assessment of residual strength and fatigue diagrams involves a comprehensive exploration of statistical relationships and uncertainties. Through the development of the EIFSD, the assessment framework is refined to provide a more accurate representation of structural integrity, thus establishing a foundation for conditioned-based inspections.

4 STRUCTURAL HEALTH MONITORING

Structural Health Monitoring (SHM) in Avatar involves placing permanent fixed sensors on structures, minimizing manual intervention, and facilitating continuous monitoring for early defect detection. This approach supports predictive maintenance for aircraft, allowing real-time analysis of in-flight loads and structural states. By employing a Digital Twin (DT) framework, flight data is continuously recorded, enabling immediate identification of damage and early warnings for part replacement. This dynamic monitoring enhances predictive accuracy, contributing to a more sustainable transportation system. The SHM concept, coupled with DT model updates, reduces uncertainty in predicting the remaining useful life (RUL) of structures. Real-time operational information is accessible through a dashboard, integrating with CAD models, and a data analytics engine processes IoT sensor data for air vehicle tracking via edge/cloud computing.

4.1 SHM DIAGNOSIS

Structural Health Monitoring (SHM) for damage diagnosis relies on predictive models to estimate damage-related responses, but challenges like input variations, noisy data, and model uncertainty can affect the reliability of the diagnosis. In the AVATAR project, two strategies are proposed to improve diagnosis reliability: Online diagnosis uses passive inspection through multiple sensors (strain gauges, accelerometers, and piezoelectric transducers) combined with machine learning techniques, like neural networks (NN), to detect structural changes and magnitudes of loads imposed on the structure during flight, providing early warnings, and on-ground active diagnosis which evaluates the structure's physical response which enhances the reliability from the pure passive systems. Both online and on-ground diagnosis use a probabilistic approach to quantify uncertainty in damage detection, evaluated through probability of detection (PoD) curves. To enhance accuracy, the experimental results are combined with digital models of structural parts which simulate guided wave interactions with damage accounting for both physical models and the uncertainty arising in experimental measurements.

4.2 SHM PROGNOSIS

To optimize air vehicle operation, understanding the current structural state and predicting remaining life is crucial. Structural Health Monitoring (SHM) involves damage diagnosis using physics-based, data-driven, or hybrid approaches. However, uncertainties in model parameters, noisy data, and model uncertainty can affect diagnosis reliability. The AVATAR project proposes two approaches for increased reliability: 1) multi-level decision making with online and offline diagnosis, 2) probability-based diagnosis incorporating uncertainty. Online diagnosis detects changes during flight using passive sensing, leveraging machine learning like convolutional neural networks (CNN). AVATAR integrates SHM diagnostics, multi-criteria decision making, and uncertainty quantification through advanced machine learning algorithms for in-flight early warning. On-ground diagnosis, as the second level, actively excites the structure, records responses, and extracts damage-sensitive features for reliability. Both online and on-ground diagnoses operate in a probabilistic framework to quantify uncertainty in damage detection. Evaluation involves using Probability of Detection (PoD) curves, utilizing digital clones to model guided wave/damage interaction numerically with uncertainties. Surrogate models replicate guided wave propagation in real structures, and advanced machine learning tools, such as Bayesian calibration, are applied for model calibration and generating a statistical sample of damage scenarios to compute model-assisted PoD.

4.3 SYSTEM REQUIREMENTS

To ensure the effectiveness of the SHM system for the proposed smart-skin, certain requirements must be met from both the data acquisition system and the sensors used for data collection.

4.3.1 SMART SKIN SENSOR GENERAL REQUIREMENTS

The general requirements for the smart skin sensors are given as follows:

- **Accuracy:** The measurements obtained from the different sensors should accurately reflect the structural deformation underway to appropriately detect structural changes and damages in the component.
- **Sensitivity**: Sensors should provide enough sensitivity to reflect the necessary changes under structural deformation, particularly those arising from the presence of damage.
- **Redundancy:** System reliability is a vital quantification for which redundant data should be available to cross-verify data and ensure continuous monitoring in the event of failure and wear-out.
- **Power efficiency:** Sensors should be designed to consume minimal power to extend their lifespan and the maintain the data acquisition's capabilities throughout the flight.
- **Durability and Repairability:** The sensors incorporated in the smart-skin should withstand the environmental (temperature, humidity, radiations) and operational (tension, compression, bending, torsion and impacts) conditions expected in the flight conditions for the demonstrators in the AVATAR project.
- **Compatibility with data acquisition system:** The different sensors integrated in the smart skin should be compatible with the output request to the data acquisition systems and, by consequence, those of the digital twin algorithm. Particularly, in the case of strain gauges, the nominal resistance should be consistent with the ones required to balance the Wheatstone Bridge required to translate the voltage output to strains. For accelerometers, these often require signal conditioners.
- **Sensor placement:** The location at which the different sensing systems in the smart skin are placed should reflect the specific physics of the structure under the different deformation mechanisms, particularly those corresponding to damage-prone and critical locations.

4.3.2 SMART SKIN NETWORK: TYPES OF SENSORS

Strain Gauges

Strain gauges are instruments which quantify the material deformation under different loading conditions by correlating the principle of electrical resistance variations with strains in a given location. These sensors provide accurate and quantitative data and are widely employed in standard mechanical testing of aeronautic structures for stress analysis and load measurement. The quantitative strain measurements provide insightful indicators on the structure's integrity and reliability to different load cases.

- Gauge length: The strain gauge's length should provide point-wise measurements for the strain in different directions (strain rosettes) to update the digital twin model.
- Gauge Resistance: Compatible with the Wheatstone bridge from the acquisition system.
- Gauge Factor: Comparable to those obtained in commercial sensors.

Accelerometers

Accelerometer sensors, by employing microelectromechanical systems (MEMs), enable the precise monitoring of acceleration forces experienced by a structure during dynamic load regimes. By converting the physical accelerations to electrical signals, these sensors provide further understanding to the dynamic behaviour from the structure particularly when the structure's resonance frequencies are excited which can compromise its integrity.

Piezoelectric Transducers

Piezoelectric transducers convert electric potentials between the two electrodes into mechanical vibrations which propagate parallel to the structure's surfaces (Lamb Waves). These waves interact with damages by altering the propagating wave's characteristics (amplitude, time of arrival, wave mode) which is captured by other sensors in the network and identified when comparing to the wave propagating through the pristine structure.

Some important characteristics when selecting the appropriate piezoelectric transducer are:

- Shape contraction: Through-thickness polarization
- Frequency Response Function: kHz – MHz range

Thickness: 0.5 to 2mm (depending on the excitation type and thickness of component)

4.4 DATA ACQUISITION SYSTEM REQUIREMENTS

The following list are the system requirements for the data acquisition.

- **High Sampling Rate:** The data acquisition must provide capabilities to capture the dynamic structural responses accurately from the aircraft under different operation environments. Generally, the Nyquist theorem dictates the sampling frequency for the current systems based on the frequency content from the sensors.
  - Strain Gauge**:** Often in the Hz region given the generally focused input from gusts and maneuvers of the aircraft
  - Accelerometer: Usually in the kHz region to detect the engine-driven excitation
  - Piezoelectric transducers: Usually placed in the MHz range given the ultrasonic frequencies at which guided waves propagate.
- **Data Transmission and Storage:** The system should provide capability to store data efficiently in long-term to provide historical analysis and comparison, data transmission is essential for immediate assessment of both diagnosis and following prognosis.
- **Remote Monitoring**: The data acquisition should be remotely controlled to trigger its acquisition or, alternatively, the acquisition starts above a certain trigger level for the observation of impact-related damages.
- **Data processing and analysis**: This requirement is necessary when some in-situ data processing and cleaning is required to ease the data transmission for final postprocessing.
- **Scalability**: The data acquisition system should provide the incorporation of additional sensors as the structure's size increases throughout the test roadmap.

In summary, an effective SHM system for the current smart skin concept requires a well-tailored data acquisition system and sensor network composed by different sensing mechanisms in locations representative of critical points to the wing's structural integrity. Meeting these requirements ensures that the system can accurately and reliably assess the health of the structural and provide insightful inputs for the Digital Twin platform.

5 AVATAR DIGITAL TWIN PROGNOSTIC MODELLING

AVATAR Digital Twin will input to established RUL concepts to demonstrate the advantages of predictive maintenance for extended safe life for three selected air vehicles:

1. **Evektor VUT100 Cobra** - manned 4-seater propeller metallic aircraft designed within the Safe-Life concept.
2. **Evektor RTC Sportstar** – manned 2-seater propeller metallic aircraft designed within the Safe-Life concept and expected extension of some parts to Damage-Tolerant concept.
3. **Nordic Wing Astero** – electrically powered, fixed-wing unmanned aerial vehicle.

These demonstrators will show the applicability of the proposed digital framework for different designs and materials. AVATAR's building block approach is illustrated in Figure 2.

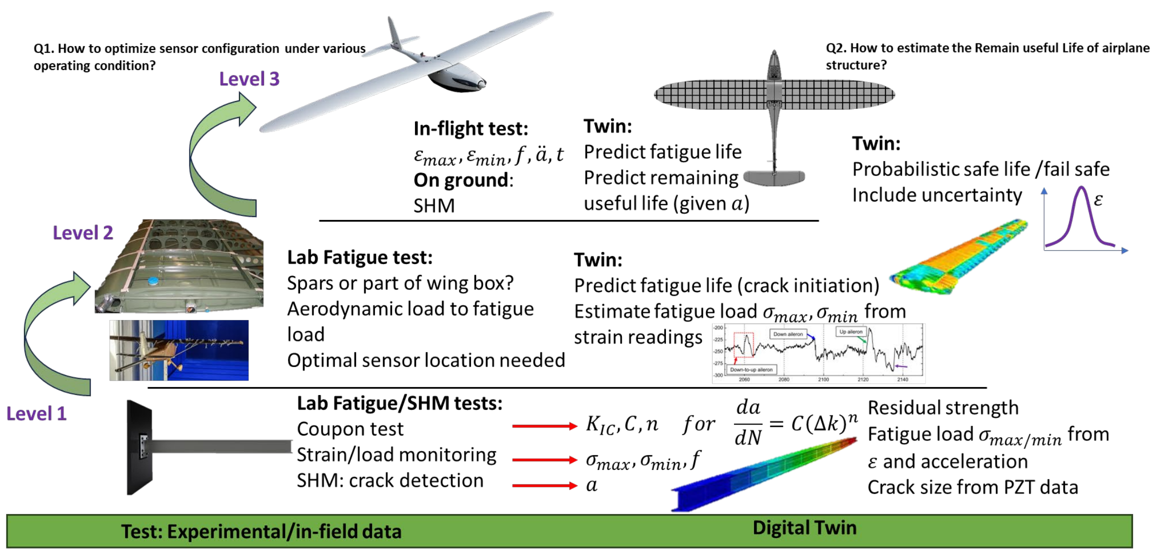

Figure 2 Building Block Approach for developing Digital Twin

The virtual system of AVATAR's DT-PdM platform consists of three major components: probabilistic diagnosis and prognosis, load spectra prediction, and optimised service life under uncertainty. The proposed virtual system is linked with the data communication platform through advanced analytics and Machine Learning (ML) tools to address the challenges of big data, data quality and availability.

5.1 PROBABILISTIC DIAGNOSIS MODULE

Optimised service life for an air vehicle requires first to quantify the current state of structure, followed by predicting the remaining useful life of the structure. SHM based damage diagnosis is an inverse problem that can be carried out using physics-base, data-driven or hybrid approaches which rely on a forward prediction model that predicts a measured damage-sensitive response (data) of the system to a known excitation of choice. Real-time diagnosis refers to passive sensing where a change in structure's response due to accidental impact, buckling, delaminations, unexpected high loads, crack initiation, etc. is detected **during flight**. On-ground detection (after each flight) is the second level of diagnosis, where the structure is actively excited via PZT transducers with a given waveform (ultrasonic wave) and its response recorded. The sensor signals will then be post-processed to extract damage sensitive features as health indicators.

5.2 PROBABILISTIC PROGNOSIS MODULE

In AVATAR prognosis refers to remaining useful life (RUL) prediction. Current practice for RUL estimation is based on historical load envelopes with conservative safety and reliability factors. Safe-life designs involve testing and analysis (typically fatigue analysis) to estimate how long the component can be in service before it will likely fail.

5.2.1 LOAD SPECTRA PREDICTION MODULE

Accurate understanding of the true load spectra the structure experienced during its service life is the key drive behind the prognosis module of AVATAR's DT platform tailored to the specific analysed airplane. The proposed Internet-of-Things (IoT) sensing skin will record the acceleration and strain responses of the structure in real-time using the integrated sensors, thus giving a representative data set related to stress and load in comparison to calculated data sets taking the conservative methodology into consideration.

5.2.2 OPTIMIZED SERVICE LIFE USING MISSION SPECIFIC LOAD SPECTRA

The proposed platform will integrate all information collected from the diagnosis and prognosis module and provide the end user with rapid health management indications. The main question the DT must answer is: If damage is not present in the structure, given its flight history and service life, is it expected to safely complete the next mission? This question requires information regarding the nature and expected loads for the upcoming flight-cycle of the monitored air vehicle.

The demonstrators used within AVATAR project relate among other to the SportStar RTC aircraft, which is certified within the LSA specification. Though this specification is stricter than it is common in the general ultralight category, it still remains quite benevolent in fatigue life estimation and RUL prognosis. The output of AVATAR thus can help to extend the service life of such aircraft to some extent, something which is not applicable for general aircraft categories, where the approved airworthiness documentation cannot be updated based on the Digital Twin output. Let us remind the reader again of the TRL 2-4 applicable to this project.

6 FUNCTIONAL REQUIREMENTS OF THE IOT SENSING SKIN

The IoT sensing skin is a network of sensor nodes (see Figure 3) and is composed of several components, including multi-sensing subsystems (e.g., acceleration sensing, loading measurements via strain gauges and temperature sensing), energy harvesters, microcontrollers, batteries, circuit boards, wireless communication modules, etc. The quantity of microcontrollers, strain rosettes, thermistors and commercial 3-axis accelerometers in one sensor node may change according to the location of the sensor node.

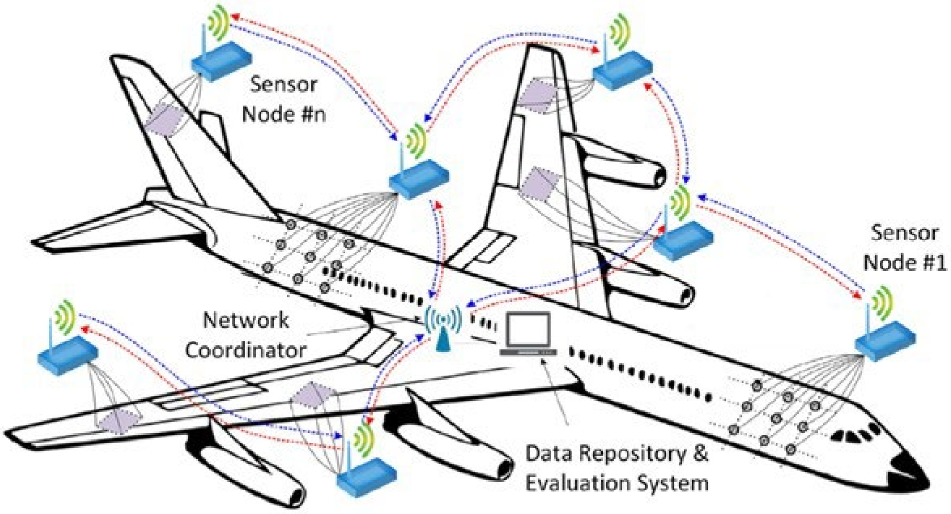

Figure 3 Schematic of the IoT sensing skin with multiple sensing nodes

Three key sensing functions will be achieved by the proposed sensing skin. They are temperature measurements using flexible printed thermistors and the associated amplifiers, stress monitoring via flexible printed strain gauges with Wheatstone Bridge Circuits, and acceleration sensing by commercial accelerometers. The design of the sensing skin depends on air vehicle operating conditions, space availability, sensing demands, as well as typical duration and frequency of transient impact or damage events.

Power consumption will be calculated and verified by experiments. The optimization of the multi-sensing subsystem and the IoT sensing skin will be carried out following the definition of demonstrators and flight tests. Methods for reducing power consumption in the IoT sensing skin, such as implementing a sleep mode for the microcontroller unit (MCU), utilizing event-triggered modes, and sending pre-processed data (containing essential features of raw measurements) to the cloud, will be implemented.

For the microcontroller unit (MCU), STM32L4 series MCU chip (or similar) will be applied because of the high performance in data acquisition (e.g, wide range of sampling rate, high accuracy when reading analogue signals), processing (e.g., FFT for a given time period of signals), and low power modes (a key feature of the selected series of the chip). It's able to deal with multiple channels of analogue signals and digital signals. The ADC channel sampling frequency of the MCU varies from very low to more than 5 Msa/s. This can meet varying requirements on sampling rate for different sensors in different sensor nodes. For example, the sampling rate for temperature sensors could be relatively low as temperature does not change quickly, while for strain gauges and accelerometers should be much higher to get dynamic load information of the aircraft.

For printed strain rosette and thermistors, advanced manufacturing process, including printing process and electronic transfer process will be adopted to ensure realization of the new sensing skin.

In printing process, PET with transfer coating, barrier and dielectric layer, conductive layer and adhesive layer are the main part of flexible electronics. The printed electronics can endure numerous stretching events, exhibit water resistance, and are fully washable. The outstanding properties of the sensing skin will enhance the performance of the multi-sensing subsystem compared to the current state of the art.

For 3 axis accelerometer, ADXL series commercial sensors which provide ranges of ±10 g and ±40 g measurements will be firstly applied. Furthermore, accelerometers with the full range ±60 g will be applied in order to monitor the UAV landing loads.

Power consumption of the sensor skin (including power consumptions for microcontrollers, wireless data transmission and sensors) will be calculated and verified by experiments. The optimization of the multi-sensing subsystem and the IoT sensing skin will be carried out following the definition of demonstrators and flight tests. Methods for reducing power consumption in the IoT sensing skin, such as implementing a sleep mode for the microcontroller unit, utilizing event-triggered modes and sending pre-processed data (containing essential features of raw measurements) to the cloud, will be implemented.

7 DATA TRANSFER AND COMMUNICATION REQUIREMENTS

As described in the section 2.1, the PdM process requires data as main input. The data will go through multiple transformations, various treatment phases and will flow through multiple systems via various interfaces. Considering the heterogeneity of the systems and interfaces to be deployed during the project, a data standardization phase is required in order to achieve the best usage of data during the PdM process.

Data transfer aims to outline the fundamental elements related to data transmission and communication requirements, with a focus on the need for precise PdM specifications. Consequently, it is imperative to thoroughly examine key considerations to establish an efficient and dependable data transmission framework. The primary objective is to develop a high-level data transmission architecture that seamlessly facilitates the exchange of PdM-related data among distinct system components.

7.1 DATA ARCHITECTURE

In order to define the baseline of the data transmission, we need **first** to identify, know, and master the **data in use and its flows**. Mastering the data is achievable via building the data architectures in scope of the project. Data architecture describes the structure of a system logical and physical data assets and data management resources. It would include details such as data names, comprehensive data and metadata definition, conceptual and logical entities and relationships, business rules, policies, and standards that govern the collection, storage, arrangement, integration, and the use of data.

The main goal of data architecture is to translate functional needs into data and systems requirements, and to manage data and its flows through these components.

Through defining the data architectures, we mainly aim to achieve two goals:

- Identify data storage, processing, and communication requirements
- Design plans to meet the current and future data requirements of the project

The following diagram highlights the different steps the project should go through in order to define the data architectures. The first step starts with defining the functional and non-functional requirements, this was defined in the previous sections of this document. Second, data should be understood (data in use, and data flows). Then the data flows will allow to understand and define the applications requirements, and hence define the needed technology to be deployed (protocols, infrastructure, interfaces…).

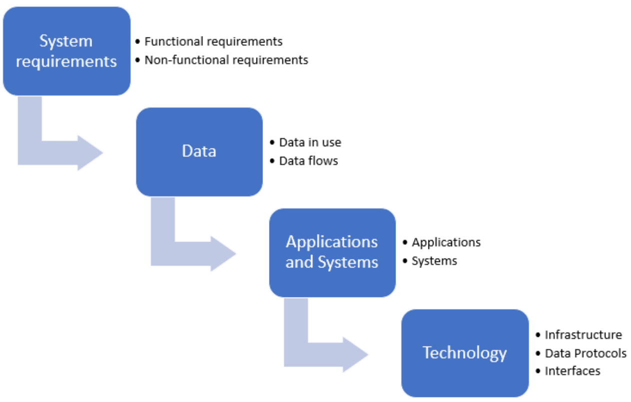

Figure 4 Data Journey from requirements till the protocol's definition

7.2 DATA ARCHITECTURE PRINCIPLES AND BEST PRACTICES

As the data architectures design the structure, and define the organization and storage of data within the systems, there are several standards and principles best practices that define how the design should be:

- **Alignment with functional objectives**
  The data architecture should be aligned with the overall business strategy and goals, ensuring that data supports the project stakeholder's objectives.
- **Seamless Data integration**
  The architecture should support the integration of data from different sources, systems, and technologies to ensure consistency and accuracy across the scope of the project. It should as well integrate with various applications using standard API interfaces, and be optimized for sharing data across systems, geographies, and actors.
- **Data security and privacy**
  Security is essential. The architecture should ensure the confidentiality, integrity, and availability of data, and comply with relevant regulations and standards.
  Moreover, modern data architectures must be designed for security, and they must support data policies and access controls directly on the raw data.
- **Scalability and flexibility**
  The architecture should be scalable to accommodate growth and changes in data volume and complexity, and flexible enough to support changing functional needs and emerging technologies.
  Data flows should be optimized for agility. We should reduce the number of times data must be moved (to reduce cost), and we should increase data freshness for better flexibility.
- **Data quality**
  The architecture should support the collection, validation, and cleaning of high-quality data to ensure its accuracy and usefulness.
- **Standardization and normalization**
  The architecture should promote standardization and normalization of data to ensure consistency, reduce redundancy, and simplify data management.
- **Data governance**
  The architecture should establish clear policies, procedures, and responsibilities for managing data throughout its lifecycle, ensuring accountability and compliance with regulations and standards.
- **Cloud-native**
  Modern data architectures should be designed to support elastic scaling, high availability, end-to-end security for data in motion and data at rest, and cost and performance scalability.
- **Real-time data enabling**
  Modern data architectures should support the ability to deploy automated and active data validation, classification, management, and governance.
- **Decoupled and extensible data**
  Modern data architectures should be designed to be loosely coupled, enabling services to perform minimal tasks independent of other services.

7.3 DATA ARCHITECTURE COMPONENTS

The following key requirements should be identified and should define how data architectures will be defined:

- **Data models:** These are the graphical or written representations of the data.

- **Data integration:** This refers to the processes and tools used to extract, transform, and load data from different sources into a unified format.
- **Data storage:** This refers to the physical or virtual storage of the data. It includes cloud and offline storage locations.
- **Data processing:** This includes the tools and technologies used to process and analyze data. Many modern data architectures make use of cloud and edge computing to analyze and manage data.
- **Data access and communication:** This refers to the mechanisms for accessing and retrieving data, including application programming interfaces (APIs), data services, and query languages.
- **Data governance**: This includes the policies, standards, and procedures for managing data throughout its lifecycle, including data quality, security, privacy, and compliance.

7.4 CONCEPTUAL AVATAR DATA ARCHITECTURE

The digital twin platform will be defined through the integration of data and services distributed over three locations:

- The aircraft services
- The cloud services
- The local (offline) services

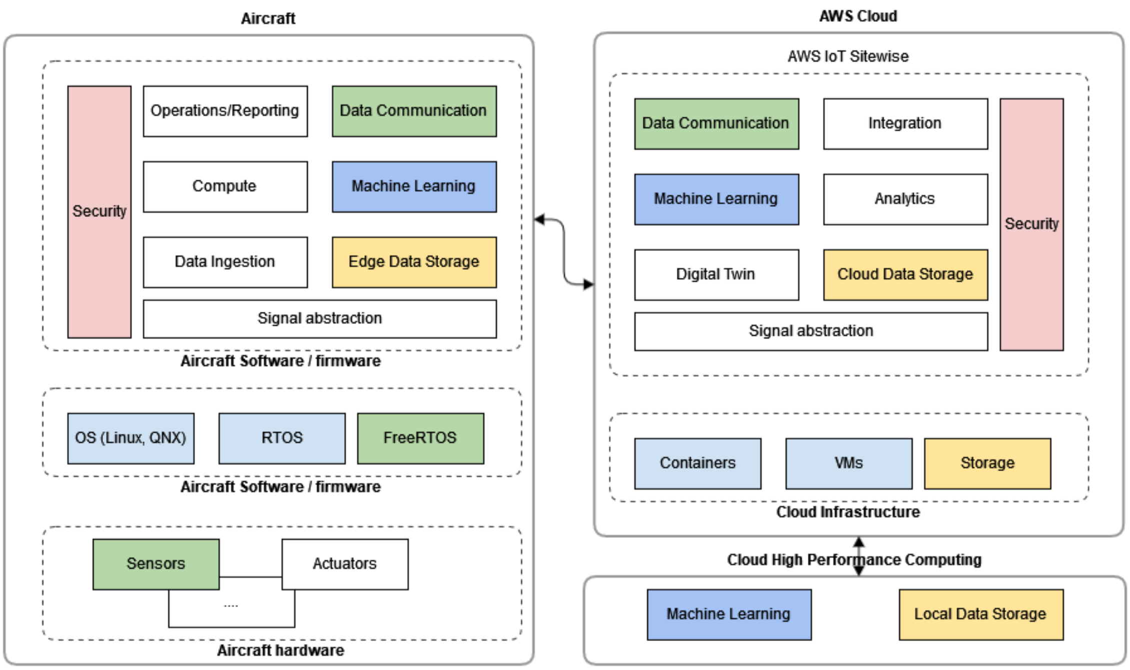

Figure 5 Conceptual Data Architecture for Avatar's Digital Twin

The figure 5 shows the list of features that should co-exists in a homogenous way in the three prementioned locations. The features that systems should consider are the following:

- Data communication (Green box): The communication should be established from the sensors till the cloud platform through different communications layers in the middle.
- Data storage (Yellow box): Data storage should be considered in the aircraft, in the cloud and also in the HPC data centers.

- Data processing: Data will have different transformation and processing requirements. More details will follow in the next paragraph.
- Security: Data and systems security should be enforced at all the layers.
- Data analytics: It will be mainly built in the cloud, and then should be available in the aircraft for real time data processing.

7.5 DATA MODELS

During the definition of the different data models, the solution should consider the following requirements:

- **Digital Twin Platform:** The DT platform should consider the following key items:
    - The main question the DT must answer is: If damage is not present in the structure, given its flight history and service life, is it expected to safely complete the next mission?
    - The virtual system of AVATAR's DT-PdM platform consists of three major components: probabilistic diagnosis and prognosis, load spectra prediction, and optimised service life under uncertainty.
    - The real-time operational information of each aircraft can be accessible through a front-end dashboard for real-time visualisation mapped against the CAD model of the structure.
- **Advanced Dashboarding:** To deliver real-time analytics, to perform analytics on new data as it arrives in the environment, to continuously monitor and update the health state of the air vehicle, a digital twin dashboard should be designed and developed to visualize the outcome to the end users. The data to be displayed are:
    - The data collected from IoT sensing skin within the aircraft
    - The prediction data generated by the ML algorithms
    - Other key performance indicators (KPIs)

  This data will be visualised through a dashboard representing the digital copy of the structure, with the log files of its operation in real time.
- **Advanced AI and Real-time analytics:** Data streaming is flowing data continuously from a source to a destination for processing and analysis in real-time or near real-time. The goal of many modern data architectures is to deliver real-time analytics, the ability to perform analytics on new data as it arrives in the environment.

7.6 DATA INTEGRATION

In AVATAR, multiple data types will be used to bring various measurements to the PdM platform. The different sensors integrated in the smart skin should be compatible with the data acquisition components and interfaces. These data types should support the following requirements (but they should not be limited only to them):

- Sensor data
    - A novel IoT sensor solution for multi-parameter sensing (acoustic emission, strain/load, temperature…).
    - Strain gauges sensors to collect strain measurements
    - Accelerometers
    - Piezoelectric Transducers
- Operational data
    - Maintenance history
    - Initial airworthiness data and operational data

  - In flight loads and operations will be recorded continuously, and the current and future states of the structure will be analysed in real time
- Airplane data: Needed to be provided one time per aircraft model to create an aircraft visualisation in DT platform
- Flight data
  - Real flight data of EVEKTOR's Cobra and SportStar RTC aircrafts
  - Real flight data of Nordic Wing's Astero electric unmanned aircraft
- Prediction data
  - Physical models: To predict state of the aircraft surface in the future
  - Surrogate models: To predict state of the aircraft surface in the future
- Alerts: To warn in real time about possible physical damage

7.7 DATA STORAGE

As highlighted in the figure 5, the system should provide capability to store data efficiently in long-term to provide historical analysis and comparison. The solution should also define the data that should never be stored, as well as the data to be stored either virtually or on physical servers.

Different data storage types should be defined based on the functional need:

- Online Databases
- Offline databases
- Data lake on the cloud for the DT platform
- Data archiving, online and offline, for historical and backup data

Data storage security standards are vital for the project to ensure system compliance.

7.8 DATA PROCESSING

Optimizing data transfer, synchronization, and processing between edge services and cloud infrastructure is critical. These computational requirements, encompassing both edge services and cloud infrastructure, are vital for the success of the advanced analytics platform. Their careful selection, configuration, and integration directly impact system performance, scalability, and the generation of valuable insights through data analysis, underscoring their fundamental role in achieving excellence in advanced analytics.

Efficient data cleaning and scalable data processing plays a foundational role for the success of the AVATAR project, especially in managing the large volumes of data generated from demonstrations and smaller-scale tests. This involves employing cutting-edge data cleaning techniques to eliminate noise, correct errors, and improve data quality. Scalable data processing methods are essential to efficiently handle substantial data streams, ensuring data is transformed, aggregated, and made accessible for subsequent analysis. These requirements also extend to the computational resources necessary for training and updating associated databases. The training process involves the use of machine learning algorithms and techniques to create predictive models based on the collected data. Similarly, updating databases involves incorporating new data to enhance the accuracy of surrogate models over time.

7.9 DATA ACCESS AND COMMUNICATION

Data acquisition and wireless communication are essential functions for IoT sensing skins to collect distributed operational data and transmit the data wirelessly to the cloud. This section defines the data access and data transfer requirements for the onboard communication (from the IoT sensing skin to the onboard gateway), as well as for the aircraft to Ground communication.

7.9.1 SATELLITE VS TERRESTRIAL COMMUNICATION

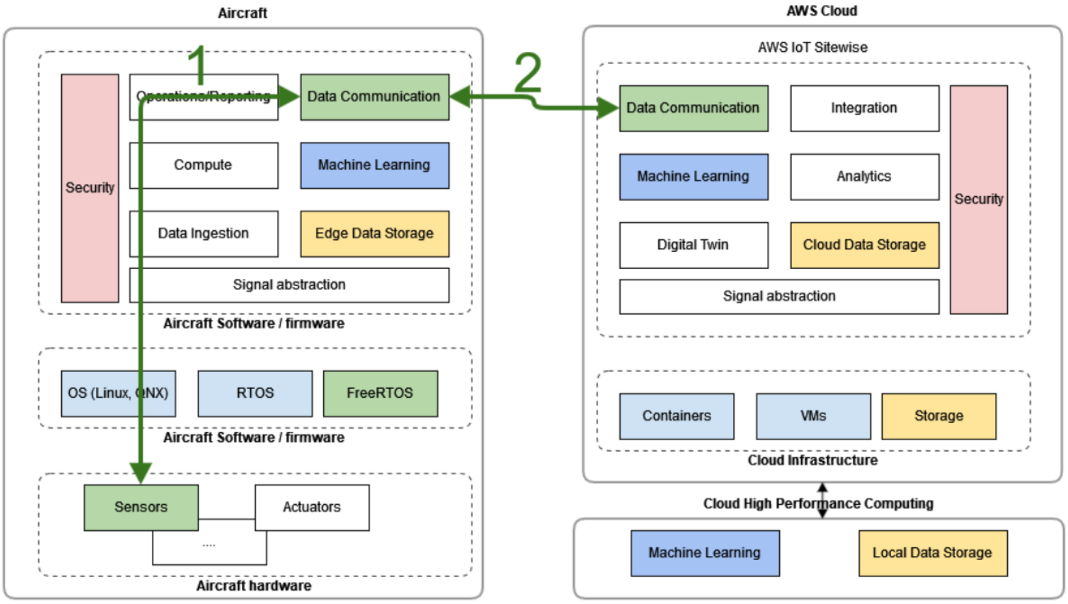

Figure 6 Data transfer in Avatar's Digital Twin

In AVATAR, the satellite-based and terrestrial-based solutions will be analysed since they can potentially complement each other. Both infrastructures are needed to achieve full-scale aeronautical connectivity solution. Terrestrial technologies are the ones that enable data transmission through a terrestrial-based infrastructure. Therefore, exploring terrestrial data links is promising to solve satellite limitations. For example, cost, delay and capacity are challenges that can be overcome by a terrestrial technology. However, the terrestrial technologies have difficulties in providing connectivity for intercontinental flights over the oceans.

A trade-off highlighting advantages and disadvantages of each technology and their compliancy with the project requirements will be performed. The trade-off will include support of different network topologies, meshed networking, autonomous adaptability to the channel conditions, maximum permissible Doppler and Doppler rate due to mobility, tolerance to latency, maximum data rate, and available bandwidths for aviation.

7.9.2 FROM THE EDGE TO THE CLOUD COMMUNICATION (LINK2)

Edge services play a pivotal role in real-time data processing, involving the careful selection of suitable edge devices, their configuration, and the development of customized applications tailored to the system's needs. Data communication (link 2 in the diagram in Figure 6) needs to be defined at hardware level as well as at software and communication protocols level. The data transfer from the edge to the cloud can be done via terrestrial based communication or via satellite links. These communication requirements should be assessed and justified according to the functional requirements defined in the previous sections of this document.

Security measures are of utmost importance to protect data at the edge. Simultaneously, the integration with cloud infrastructure is highlighted to create a unified data processing environment. Cloud infrastructure is also essential for scalability and computational resources needed for complex analytics. Key considerations include selecting the right cloud services, provisioning computational resources, ensuring data security and compliance, and addressing data storage, backup, and disaster recovery.

7.9.3 FROM THE SENSOR TO THE EDGE COMMUNICATION (LINK1)

Overall block diagram of the airplane sensor network is presented in Figure 7. Each sensor node is responsible for measuring the desired Analog signals and send it to the microcontroller/processor for digital conversion. Then after applying some signal processing algorithms, the output should be sent to the gateway wirelessly. This part is the responsibility of the wireless network to collect the data from sensor nodes at the gateway and make it available for the AWS cloud for further analysis.

Sensor block (the pink square box) can be divided into 2 sub-systems:

- Sensor sub-system, which contains the sensor hardware and the microcontroller in charge of analog to digital conversion of sensor's outputs, post-sampling processing and data transmission to the wireless node to send the data to the gateway.
- Wireless node sub-system, which is responsible for receiving data from sensor sub-system and transmit the data over the air to the gateway.

In order to decrease the system complexity, power consumption and reduce the area, it would be better to have both sensor and wireless communication subsystems on a single hardware.

Gateway block (the green box) can also be divided into 2 sub-systems:

- Wireless gateway sub-system, which is responsible for receiving data from sensors and send it to the gateway PC. Note, that it is desired (not mandatory) to be able to have a mesh networking topology. In this case wireless nodes can also have the gateway role which is called relay function. It is necessary for Wireless Gateway to also support the libraries of FreeRTOS which is compliant with AWS cloud interface.
- Gateway PC, which is responsible for receiving data from all sensors, save the data in a storage and send it to the AWS cloud for further analysis while the airplane is on the ground.

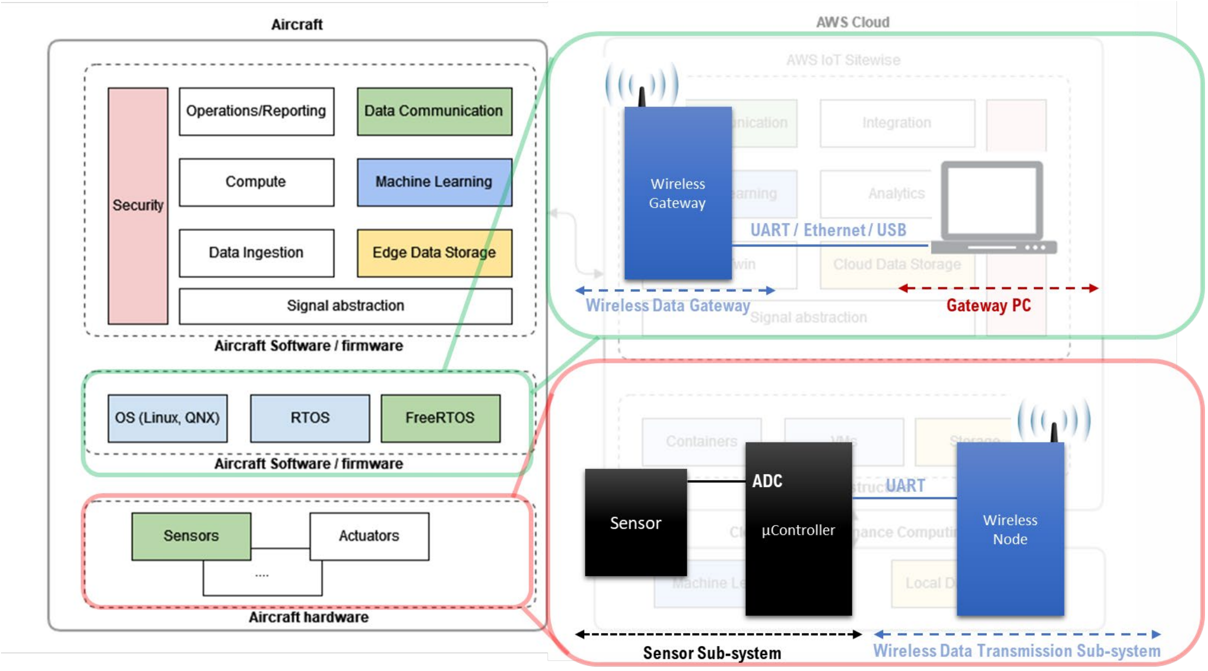

Figure 7: Detailed block diagram of the communication system from sensor to the gateway

There are several features which nodes should support as it is presented in Figure 8.

- **Wireless connectivity**: The main feature for the target device for both sensor nodes and the gateway is to have wireless connectivity. This feature gets more important in scope of AVATAR project because the sensor nodes are embedded in different locations in the airplane body and so it is not possible to have wired connection. It is also desired to be able to update the firmware running on the nodes wirelessly for the same reason.
- **ADC channels**: As the information coming from sensors are analog, there must be some ADC channels available to convert analog signals to digital for further signal processing and digital wireless transfer.
- **FreeRTOS**: This operating system makes it much easier to interact with the AWS cloud for data transmission. FreeRTOS is only supported by some microprocessors available in the market.
- **Number of nodes**: As we have several sensor nodes and they will transfer the data to the gateway at the same time, both nodes and the gateway should support the functionality in this arrangement. For the nodes, they should be able to send the data without making any interference with the rest as some maybe be close to each other in the sense of distance. For the gateway, it should be able to connect and receive data coming from multiple nodes at the same time.
- **Power consumption**: As it is not possible to deliver the power rails to all nodes and low power consumption for the aviation is vital, nodes should consume as low power as possible whether they are connected to the battery or to the airplane power distribution system.
- **Frequency band**: The ISM radio bands are portion of the radio spectrum reserved internationally for industrial, scientific, and medical (ISM) purposes. This radio band is chosen for AVATAR as it is safe not to interfere with the rest of applications running on the airplane. This radio band is in the range of 2.4GHz – 2.5GHz.

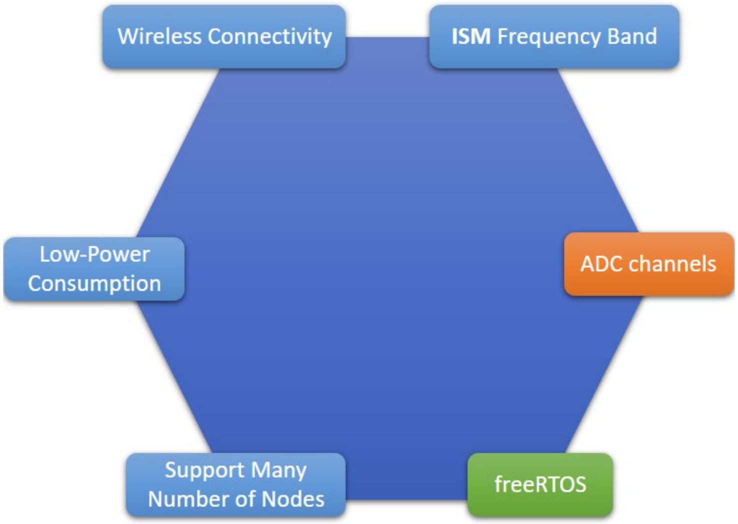

Figure 8: Key requirements for the nodes

For the wireless connectivity, there are multiple options based on:

- Frequency band
- Maximum Data Rate
- Maximum Range
- Power Consumption
- Supported Topology

A complete comparison regarding above features among available wireless protocols are presented in Table 1. In the following, we are going to narrow down the candidates based on AVATAR requirements.

Table 1: Wireless technology candidates

Technology		Frequency	Data Rate	Range	Power Usage	Topology
802.11	Wi-Fi	sub-GHz (802.11ah)	up to 346.667 Mbps	up to a km	Medium	Star
	Wi-Fi 6	2.4 and 5Ghz (802.11ax)	up to 9.607 Gbps	up to 35m (single router)	High	Star
802.15.1	Bluetooth(802.15.1)	2.4GHz	1,2,3 Mbps	up to 90 m	Low	Piconet and Mesh
802.15.4		868 MHz (EU) /915 MHz (NA)	250 kbps			
	Zigbee	2.4GHz	250 kbps	up to 90 m	Low	Mesh, Star, Cluster
	WirelessHART	2.4GHz	250 kbps	up to 90m	Moderate	Mesh
	6LoWPAN	2.4GHz	250 kbps	up to 100m	Moderate	Star
	ISA100.11a	2.4GHz	250 kbps	up to 500m	Moderate	Mesh, Star, Cluster
	Thread	2.4GHz	250 kbps	up to 30m	Low	Mesh
Cellular	GPRS	380 to 1900 MHz	128.4 kbps	several kms	High	Star
	EDGE	380 to1900 MHz	355.5 kbps	several kms	High	Star
	3G-HSDPA	700MHz to 3GHz	14.4 Mbps	several kms	High	Star
	3G-HDPA+	700MHz to 3GHz	337 Mbps	several kms	High	Star
	LTE-Cat1	600MHz to 6GHz	10 Mbps	several kms	Moderate	Star
	LTE-CatM1	600MHz to 6GHz	1 Mbps	several kms	Low	Star
	NB-IoT	600MHz to 6GHz	250 kbps	several kms	Low	Star
	5G	600MHz to 6GHz	20 Gbps	several kms		Star
		24-86Ghz	20 Gbps	several kms		Star
Z-wave		868.42MHz (EU) / 908.42MHz (NA)	40 kbps	up to 30m	Low	Mesh
LoRaWAN		868.42MHz (EU) / 908.42MHz (NA)	up to 50 kbps	several kms	Low	Star
SigFox		868MHz (EU) /902MHz (NA)	600 bps	up to 800m	Low	Star
ISO 18000	NFC	13.56MHz	106 to 424 kbit/s	10cm	Low	P2P
	RFID	125 kHz to 134 kHz; 6.7 MHz; 27MHz;	106 to 424 kbit/s	up to 10 cm	Low	
		433MHz	848 kbps	1-100m		
		865 to 868 MHz (EU); 902 to 928 MHz (NA)		1-12m		
		2.45 GHz		1-2m		
		5.8 GHz		up to 200m		
		24.125 GHz		up to 200m		

Note, that for Bluetooth protocol the device should support BLE (Low Energy Bluetooth)-Mesh. It is because via Bluetooth up to 7 devices can be connected while BLE can connect 32768 devices which is limited to the address bits of 15 (Kuan, 2023).

7.9.4 RADIO BAND

As it is mentioned, ISM radio band is chosen to be the target band in the frequency range of 2.4GHz and 2.5GHz. So remaining candidates would be: Wi-Fi, Bluetooth (BLE), Zigbee, Wireless HART, Thread, and RFID.

7.9.5 MAXIMUM DATA RATE

To have a rough estimation of the required Data Rate in AVATAR, we need to make some assumptions about “sampling rate”, “ADC resolution bits” and “number of nodes”.

Because of the requirements mentioned in previous chapters, AVATAR is defined as a low-data-rate wireless application, so each node should transmit data less than 10Kbit/second. It means that with 25 number of nodes, it will touch the 250Kbit/second. Number of nodes is related to the size of airplane and the accuracy of measurement of the airplane surface. RFID will be rejected in this step and remaining candidates would be Wi-Fi, Bluetooth (BLE), Zigbee, Wireless HART, and Thread.

7.9.6 MAXIMUM RANGE

It is assumed that 20 meters is the maximum distance between 2 nodes or between a node and the gateway. All remaining candidates support this requirement.

7.9.7 POWER CONSUMPTION

Power consumption is a critical concern in AVATAR. Wi-Fi is a power-hungry protocol which can has up to 10 times more power consumption than low-energy protocols like Bluetooth. But we should not ignore the high-data-rate capability of this protocol. It is better to keep Wi-Fi feature for final device for firmware upgrade channel not for sensor data transmission protocol.

So, Wi-Fi will be rejected in this step and remaining candidates would be Bluetooth (BLE), Zigbee, Wireless HART, and Thread.

7.9.8 NETWORK TOPOLOGIES

Network topology defines the arrangement of connectivity between nodes and the gateway and among the nodes.

Star topology which is the most common topology between both wired and wireless networks forces all sensor nodes to directly communicate with the wireless gateway to send their data Figure 9. The disadvantage of Star is that all the sensors should not be farther than the maximum over-the-air transmission distance while the advantage is to keep the connectivity with least complexity and easy to handle.

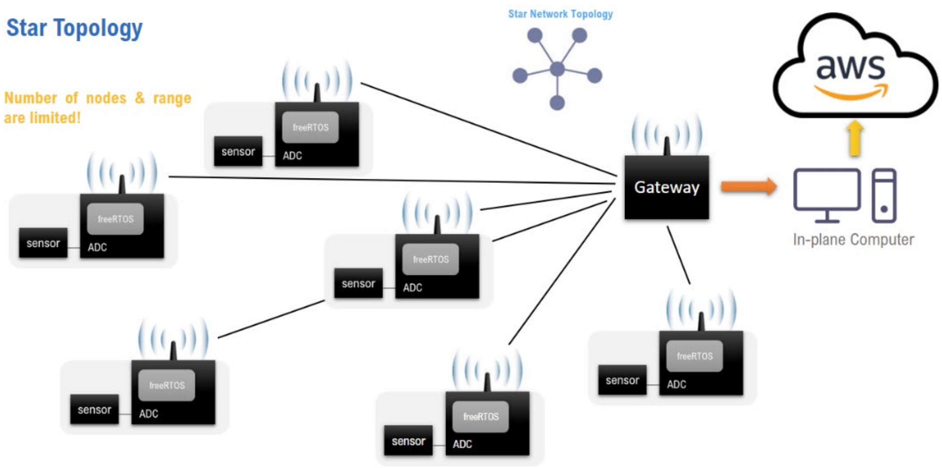

Figure 9: Star topology for sensor nodes

Mesh topology lets sensor nodes to also act as relays for the rest to communicate with the gateway. But this feature is only available in some products in the market Figure 10.

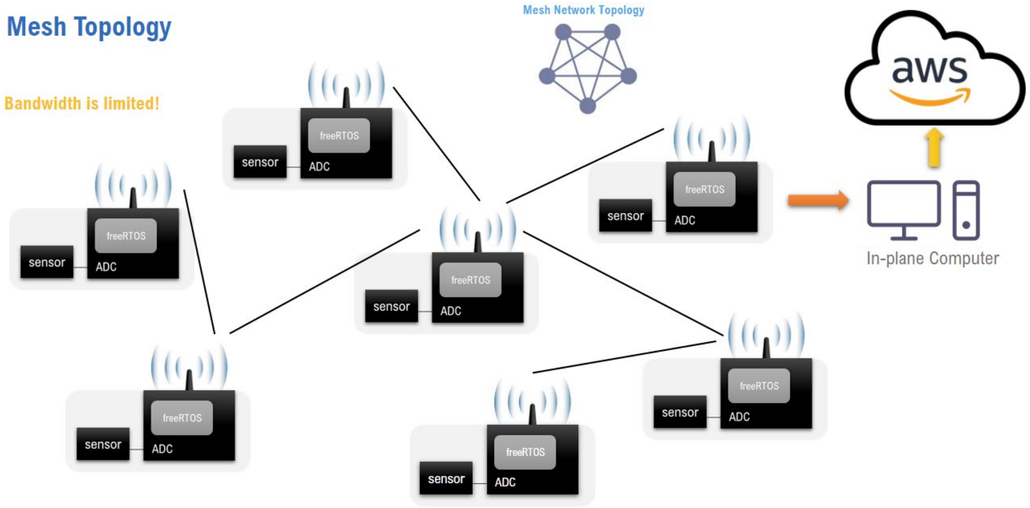

Figure 10: Mesh topology for sensor nodes

All remaining candidates support Mesh networking which is desired in AVATAR. So remaining candidates would be Bluetooth (BLE), Zigbee, Wireless HART, and Thread.

7.10 DATA GOVERNANCE AND SECURITY

Data storage security is critical from a legal compliance perspective. Data that organizations may use for litigation must be both secure and easily accessible.

As new data sources are added, and existing data sources get updated or modified, maintaining a record of the relationships within and between datasets becomes more and more important. These relationships might be as simple as the renaming of a column, or as complex as joining multiple tables from different sources, each of which might have several upstream transformations themselves.

Like any new system, the proposed Digital Twin Platform deals with the following security basics:

- **Confidentiality**: to ensure that data exchanged is inaccessible to unauthorized users. The users could be applications, processes, other systems and/or humans. When designing a system, adequate control mechanisms to enforce confidentiality should be in place, as well as policies that dictate what authorized users can and cannot do with the data. The more sensitive the data, the higher the level of confidentiality. Therefore, all sensitive data should always be controlled and monitored.
- **Integrity**: to ensure that a system and its data has not suffered unauthorized modification. Integrity protection protects not only data, but also operating systems, applications, and hardware from being altered by unauthorized individuals.

Availability: to guarantee that systems, applications, and data are available to users when they need them.

8 ADVANCED ANALYTICS PLATFORM: COMPUTING REQUIREMENTS

To establish a robust Predictive Maintenance framework, it is crucial to systematically outline the fundamental computational requirements of an advanced analytics platform. This process begins with a thorough examination of critical components, particularly focusing on edge services and cloud infrastructure.

The data processing phase includes several key steps. Initially, data is gathered from various data sources and examined to understand its structure. Missing or non-numeric data is addressed through methods like imputation or removal, and categorical variables are converted into numerical representations. Data transformation includes identifying different domains or regimes within air operations, clustering them, standardizing data formats, and converting units for consistency. Feature engineering focuses on extracting health indicators and continually validating data accuracy. Finally, a testing and feedback tool is used to ensure data cleaning processes do not introduce errors, with ongoing feedback mechanisms and key prognostic metrics to iteratively refine data cleaning strategies, ultimately ensuring the safety, reliability, and efficiency of air vehicles.

These requirements also extend to the computational resources necessary for training and updating associated databases. The training process involves the use of machine learning algorithms and techniques to create predictive models based on the collected data. Similarly, updating databases involves incorporating new data to enhance the accuracy of surrogate models over time.

8.1 DATA CLEANING AND DATA PROCESSING

Data cleaning involves processes such as handling missing values, removing duplicates, standardizing formats, and dealing with outliers. Below, we provide a high-level overview of data cleaning models for the air vehicle data:

- Data Acquisition and Inspection
  - Collect the data from various sources on the project
  - Begin by inspecting the raw data to understand its structure and contents
- Handling Missing, (NaN) or Non-Numerical Data
  - Identify missing or (NaN) data points and decide how to handle them.
  - Apply Common methods include imputation (filling in missing values with estimates), removal of rows or columns with missing data, or flagging missing values for special treatment during analysis.
  - If there are categorical variables, convert them into numerical representations using techniques like one-hot encoding or label encoding.
- Transform Data
  - Identify whether data spans multiple domains or regimes within air operations.
  - If it encompasses different regimes, cluster them and utilize standardization and reassembling techniques
  - Standardize and transform data formats for consistency (such as the Z-score).
  - Convert units (e.g., meters to feet) and ensure that date and time information is in a uniform format.
- Feature Engineering for health indicators
  - Understand features that may be more informative for the predictive maintenance analysis and modelling.
  - Continuously validate the cleaned data to ensure it remains accurate and consistent.
  - Identify and extract critical health indicators from the operations of aircraft. These health indicators encompass a broad spectrum of factors, including but not limited to wear and tear patterns, the progression of degradation, modes of faults, any decline

in overall performance metrics, the initial performance upon aircraft startup, and the thresholds at which system failures may occur. The analysis of these indicators plays a pivotal role in ensuring the safety, reliability, and efficiency of air vehicles, thereby enhancing both operational performance and maintenance practices.

- Testing and Feedback Tool
  - Thoroughly test data cleaning processes to make sure they do not introduce errors or bias into the data.
  - If you have a large and continuous stream of data, consider setting up automated pipelines and data-cleaning scripts to maintain data quality.
  - Establish an ongoing feedback mechanism enriched with key prognostic metrics in order to foster a continuous and iterative process of enhancing and refining data cleaning strategies. This iterative approach leverages the insights derived from these prognostic metrics to facilitate the consistent improvement and optimization of data cleaning practices over time.

8.2 THE COMPUTING REQUIREMENTS FOR THE TRAINING

A hybrid surrogate model combines elements of both machine learning models and domain specific heuristics to predict and optimize complex systems. To effectively train and update such a model, especially when dealing with large datasets, it’s essential to consider the computing requirements involved.

- Hardware Infrastructure
  - HPC to train numerical models
  - HPC to train surrogate model
  - AWS Cloud provider
- Software Frameworks
  - Machine Learning Frameworks: Use popular frameworks like TensorFlow, PyTorch, or scikit-learn to develop and train machine learning models
- Data Preprocessing Tools
- Data Storage
  - Sensor’s data to be stored on the edge, in the aircraft
  - Sensor’s data to be stored and processed in the cloud
  - Flight data to be uploaded and stored in the cloud

8.3 SPECIFIC REQUIREMENTS

The following requirements are regarded as items which the project need to address in order to satisfy a functioning platform.

- Algorithmic Requirements: Create PM algorithms that are finely tuned for efficiency and resource utilization in both edge and computing setups, while also being adaptable to meet the specific requirements of either the aircraft systems or prognostic metrics
- Programming Requirements
- Data Handling: Before the full deployment, commence with initial PM models by employing smaller or scaled-down datasets to evaluate the algorithm’s performance and meet the operational needs of the aircraft
- Cloud Integration

9 DEMONSTRATORS

9.1 VUT100 COBRA

It is a manned 4-seater propeller metallic aircraft designed within the Safe-Life concept and produced by Evektor, spol. s r. o. The test flights will be performed on the more powerful VUT100-131i Cobra aircraft with matriculation OK-RAF, see **Fejl! Henvisningskilde ikke fundet.**.

Figure 11 Evektor Cobra

9.1.1 TECHNICAL DATA

The aircraft performance parameters and dimensions are summarized in Table 1 Technical specifications of Cobra in its 131i variant related to OK-RAF airplane.

Table 2 Technical specifications of Cobra in its 131i variant related to OK-RAF airplane

Parameter	Value
Length	8.2 m
Wing span	10.50 m
Height	2.66 m
Seats	4
Design load factors	+4.5g / -2.5g
Operational load factors	+3.8g / -1.52g
Engine	Lycoming IP-580-B1A
• type	6-cyl. horizontally opposed
• max. continuous power	235 kW at 2700 rpm
• performance cruise	176 kW at 2400 rpm
• economy cruise	141 kW at 2200 rpm
• idle	1000-1200 rpm based on circumstances
• cylinder head temperature	max. 240 °C
Propeller	3 blades, MTV-9-B (MT-Propeller Entwicklung GmbH)
• propeller drive ratio	1.00
Rate of climb	5 m/s
Max. cruise speed	325 km/h
Stall speed	103 km/h
Standard range	1850 km
Fuel tank capacity	340 litres
Maximum take-off weight	1450 kg
Max. weight in baggage compartment	60 kg
Useful load	550 kg

9.1.2 TYPICAL OPERATION

The typical flight used currently for fatigue evaluations is based on the parameters provided in Table 3 Operational parameters of a typical flight. The flight profile is simplified according to AC23-13A (FAA, 2005) and the flight conditions can differ flight by flight depending on the aircraft crew, volume of tanked fuel, or atmospheric conditions.

Table 3 Operational parameters of a typical flight

Parameter	Value
Average flight weight	1318 kg
Center of gravity	29.2% SAT
Average flight speed	300 km/h
Flight height	1000 m
Typical duration of flight	40 min
Maximum Gust Load Factors	+4.5g / -2.5g
Maximum Manoeuvre Load Factors	+3.8g / -1.52g
Ratio of take-offs from concrete/grass	70/30 %

Cobra airplane is approved to perform the following manoeuvres:

- Steep turns up to bank of 60°
- Climbing turns up to bank of 60°

- Lazy eights up to bank of 60°
- Stall (except for steep stalls)
- Normal flight maneuvers

9.1.3 COMPLIANCE TO CERTIFICATION

The certification of the aircraft within the Safe Life domain is supposed to be done towards EASA. The code to conform is CS23 “Certification Specifications for Normal, Utility, Aerobatic, and Commuter Category Aeroplanes” (EASA, 2003) . As regards the fatigue life evaluation, CS23.572 is the key paragraph to follow in the case of Cobra aircraft.

9.1.4 LOAD SPECTRA

The load spectra used for all analyses conform to the standardized inputs recommended by AC23-13A (FAA, 2005) for the phases of:

- Flight
    - Gust spectrum (Fig. A1-1 of (FAA, 2005))
    - Manoeuvre spectrum (Fig. A1-2 of (FAA, 2005))
- Landing Impact Spectrum (Fig. A1-15 of (FAA, 2005))
- Taxi Spectrum (Fig. A1-16 of (FAA, 2005))

9.1.5 SERVICE LIFE OF CRITICAL PARTS

For the components which will be observed and analyzed in the AVATAR project, the specific service life intervals are set to:

- Wing and center wing box – 15,000 flight hours
- Engine mount – 6,000 flight hours
- Horizontal and vertical tail units – 15,000 flight hours

9.1.6 EXPECTED SCOPE OF IMPLEMENTING THE DIGITAL TWIN CONCEPT

Implementation of the DT concept is expected to concern above all:

- Main spar of the wing
- Main spar of the center wing box
- Engine mount
- Horizontal and vertical tail units

9.1.7 OPERATIONAL AND ENVIRONMENTAL CONDITIONS FOR THE IOT SKIN

The operational and environmental conditions for the Cobra aircraft are given in the table below.

Table 4 Operational conditions for the IoT skin on the Cobra

Parameter		Value	
		Minimum	Maximum
Temperature [degC]	Fuselage, wings	-40	60
	Engine, engine mount	-40	100
Acceleration [m/s^2]		-10	10
Strain value [%]	Aluminum parts	-0.2	0.2
	Steel parts	-0.3	0.3
Environmental influence		Continental climate conditions, occurrence of rain, snow, moisture	
Typical duration of flight [min]		15	75
Weight of the whole setup [kg]			20

For the wireless data transmission, ISM bands are preferred to avoid the bandwidths allocated to the aeronautical radionavigation. The 2.45 GHz, 5.8 GHz frequencies are preferred.

The acquisition frequency should be governed by the excitations caused by the engine operation and by the vortex induced by the propeller. The effects of gusts or of manoeuvrings will be active on much lower frequencies and they will not be decisive in this aspect. Taking into account these two load sources:

- Sampling frequency of 50 Hz is deemed appropriate for parts affected above all by the gusts and manoeuvers (close to the centre of gravity).
- Sampling frequency of 400 Hz at least could better monitor the excitations invoked by the engine and propeller.

More exact values will be provided in Deliverable 1.2 (Papuga, 2024) after the two flights with Cobra aircraft will be properly evaluated.

9.1.8 SUITABLE SENSOR LOCATIONS

The monitored parts of the aircraft might cover:

- Accelerations at the centre of gravity
- Accelerations at the engine mount
- Vertical acceleration at the main spar of the centre wing box
- Vertical acceleration at the wing half-span
- Accelerations at the root of the vertical tail unit
- Vertical acceleration at the horizontal stabilizer
- Strains at the main spar of the wing close to the wing suspension

9.1.9 SENSOR ACCESSABILITY

Because the project is of TRL2-4, and the specific used aircraft is fully built and operated, the installation will not attempt to hide itself unless this is feasible without substantial structural changes. The locations will thus be chosen so that the installation or reinstallation would not be excessively demanding. This will ensure that even the newly-printed sensors will be quickly replaceable once false readings are detected.

9.2 SPORTSTAR RTC

It is a manned 2-seater metallic aircraft designed within the Safe-Life concept within the LSA category. It is produced by Evektor, spol. s r. o., see Figure 12 Evektor SportStar RTC. Test flights will be performed with the SportStar RTC aircraft with matriculation OK-INJ.

Figure 12 Evektor SportStar RTC

9.2.1 TECHNICAL DATA

The aircraft performance parameters and dimensions are summarized in Table 4 Technical specifications of SportStar RTC OK-INJ airplane.

Table 5 Technical specifications of SportStar RTC OK-INJ airplane

Parameter	Value
Length	5.98 m
Wing span	8.65 m
Height	2.48 m
Seats	2
Design load factors	+6g / -3g
Operational load factors	+4g / -2g
Engine	Bombardier Rotax 912 iS
• type	4-cyl. horizontally opposed
• max. continuous power	69 kW at 5500 rpm
• max. take-off power	73.5 kW at 5800 rpm (for 5 minutes)
• idle	min. 1400 rpm
• cylinder head temperature	max. 128 °C
Propeller	3-blade propeller Woodcomp Klassic 1700/3/R
• propeller drive ratio	2.43
Fuel tank volume	120 litres
Rate of climb	4.5 m/s
Max. speed	212 km/h
Cruise speed	171 km/h
Stall speed	78 km/h
Standard range	1300 km
Maximum take-off weight	600 kg
Max. weight in baggage compartment	25 kg
Empty weight	355 kg

9.2.2 TYPICAL OPERATION

This type of aircraft is typically used in flight schools. This type of operation is demanding on the number of landings per flight hour, which reaches values around 3. The typical flight used currently for fatigue evaluations is based on the parameters provided in Table 5 Operational parameters of a typical flight of the RTC SportStar aircraft. The flight profile is simplified according to AC23-13A (FAA, 2005) , and the flight conditions can differ flight by flight depending on the aircraft crew, volume of tanked fuel, or atmospheric conditions.

Table 6 Operational parameters of a typical flight of the RTC SportStar aircraft

Parameter	Value
Average flight weight	556 kg
Average flight speed	208 km/h
Typical duration of flight	18 min

SportStar RTC airplane is approved to perform the following manoeuvers:

- Steep turns up to bank of 60°
- Climbing turns
- Lazy eights
- Stall (except for steep stalls)
- Normal flight maneuvers

9.2.3 COMPLIANCE TO CERTIFICATION

The aircraft is certified by EASA within the LSA category. The code to conform is CS-LSA Initial issue 27 June 2011 (EASA, 2011), Standard Specification for Design and Performance of a Light Sport Airplane (ASTM, 2023). The design and verification follow Advisory Circular AC23-13A (FAA, 2005). Fatigue, fail-safe, and damage tolerance evaluation of metallic structure for normal, utility, acrobatic, and commuter category airplanes (FAA, 2005).

In order to understand maximum potential aircraft fatigue life as well as in order to increase passenger safety, the damage tolerant approach described within CS23.573(b) (EASA, 2003) is planned to be applied on the wing structure during the AVATAR project.

9.2.4 LOAD SPECTRA

The load spectra used for all analyses conform to the standardized inputs recommended by AC23-13A (FAA, 2005) for the phases of:

- Flight
    - Gust spectrum (Fig. A1-1 of (FAA, 2005))
    - Manoeuvre spectrum (Fig. A1-2 of (FAA, 2005))
- Landing Impact Spectrum (Fig. A1-15 of (FAA, 2005))
- Taxi Spectrum (Fig. A1-16 of (FAA, 2005))

9.2.5 SERVICE LIFE OF CRITICAL PARTS

Considering selected certification process to comply with in the LSA category, the service life of the aicraft focuses the wing and tail units, which are designed to 7,000 flight hours.

9.2.6 EXPECTED SCOPE OF IMPLEMENTING THE DIGITAL TWIN CONCEPT

Implementation of the DT concept might concern above all:

- Main spar of the wing
- Main spar of the center wing box
- Engine mount
- Horizontal and vertical tail units
- Main landing gear

9.2.7 OPERATIONAL AND ENVIRONMENTAL CONDITIONS FOR THE IOT SKIN

The table below shows the operational and environmental conditions expected for the RTC Sportstar aircraft.

Table 7 Operational conditions which of the IoT skin on the RTC Sportstar aircraft

Parameter		Value	
		Minimum	Maximum
Temperature [°C]	Fuselage, wings	-10	50
	Engine, engine mount	-10	90
Acceleration [m/s^2]		-10	10
Strain values [%]	Aluminum parts	-0.3	0.3
	Steel parts	-0.2	0.2
Environmental influence		Continental climate conditions, occurrence of rain, snow, moisture	
Typical duration of flight [min]		5	60
Weight of the whole setup [kg]			20

For the wireless data transmission, ISM bands are preferred to avoid the bandwidths allocated to the aeronautical radionavigation. The 2.45 GHz, 5.8 GHz frequencies are preferred.

The acquisition frequency should be governed by the excitations caused by the engine operation and by the vortex induced by the 3-blade propeller. The effects of gusts or of manoeuvring will be active on much lower frequencies and they will not be decisive in this aspect. Taking into account these two load sources:

- Sampling frequency of 50 Hz is deemed appropriate for parts affected above all by the gusts and manoeuvres (close to the centre of gravity).
- Sampling frequency of 600 Hz at least could better monitor the excitations invoked by the engine and propeller.

More exact values will be provided in Deliverable 1.2 (Papuga, 2024) after the two flights with SportStar RTC aircraft will be properly evaluated.

9.2.8 SUITABLE SENSOR LOCATIONS

The monitored parts of the aircraft might cover:

- Accelerations at the centre of gravity
- Accelerations at the engine mount
- Vertical acceleration at the wing half-span
- Accelerations at the root of the vertical tail unit

- Vertical acceleration at the horizontal stabilizer
- Accelerations at the main landing gear leg close to the wheel axis
- Strains at the main spar of the wing close to the wing suspension

9.2.9 SENSOR ACCESSABILITY

Because the project is of TRL2-4, and the specific used aircraft is fully built and operated, the installation will not attempt to hide itself unless this is feasible without substantial structural changes. The locations will thus be chosen so that the installation or reinstallation would not be excessively demanding. This will ensure that even the newly-printed sensors will be quickly replaceable once false readings are detected.

9.3 ASTERO

The Nordic Wing Astero is an electrically powered fixed-wing unmanned aerial vehicle. Originally developed as a civil mapping and surveying drone, the Astero has evolved into the military segment, now primarily solving Intelligence, Surveillance and Reconnaissance (ISR) missions.

The Astero is powered by an 850W electric motor, operated by a mobile two-person crew for advanced ISR capabilities, including high-optics camera options, anti-jamming capabilities and ability to fly in GPS-denied areas.

The Astero is a combination of advanced structures and electronics coupled with commercial-off-the-shelf (COTS) parts from the Remote Control (RC) segment.

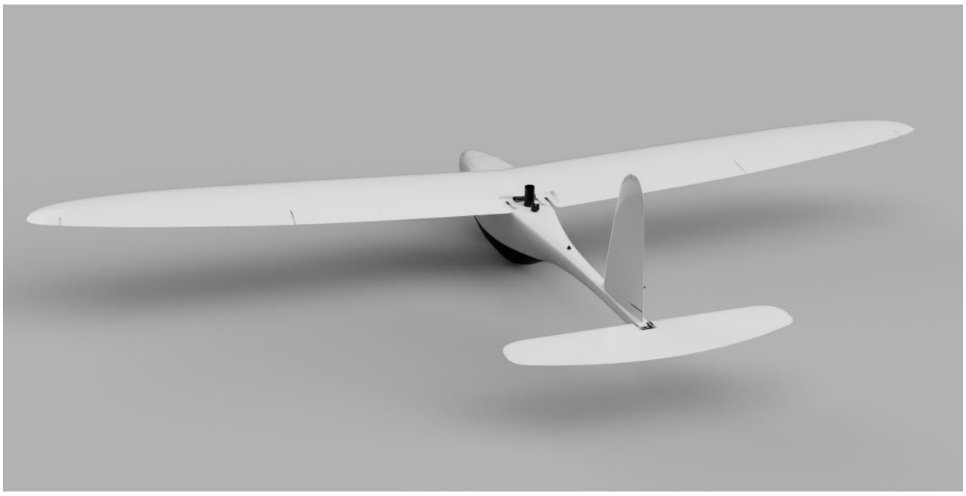

Figure 13 ASTERO Rendering

9.3.1 TECHNICAL DATA

The aircraft technical data is summarized in the table below:

Table 8 Technical Specifications of the Astero

Parameter	Value
Length	1.18 m
Wing span	2.33 m
Height	0.44 m
Seats	0
Design load factors	N/A
Operational load factors	N/A
Engine	T-Motors U5 KV400
• type	Electric
• max. continuous power	850W
Propeller	Aero-Naut 16x8” (CAM-Z)
Rate of climb	~4.5 m/s
Max. speed	~19 m/s
Cruise speed	~14-16 m/s
Stall speed	~11 m/s
Standard range	~135 km
Maximum take-off weight	4.5 kg
Empty weight	3.8 kg

9.3.2 TYPICAL OPERATION

The Astero is typically launched for ISR missions under varying conditions. The aircraft is hand launched and lands by deep stalling. The operation is semi-autonomous, allowing for the crew to set the route via the flight computers and uploading the mission to the aircraft. The aircraft then completes the mission by itself and lands in the designated spot. During the mission, the crew has full control of the drone and can change the mission and control camera equipment.

The deep stall landing consists of the following phases. When the aircraft returns from its mission, it enters the descent circle and descents to designated altitude. The aircraft then enters the landing funnel, having estimated the wind speed and direction. At the designated altitude, the aircraft slows down and approaches stall speed. Over the landing spot, the aircraft deflects full elevator up, flipping the aircraft into the deep stall. The aircraft then descends near vertically to the ground in the deep stall, with the wings acting as a parachute. This lands the Astero with high accuracy and protects the equipment on board.

9.3.3 COMPLIANCE TO CERTIFICATION

The Astero is not certified in any category and is operated under the Open Category in accordance with regulation EU 2019/947. Certain operations may require the drone to be operated in the specific category, but this applies for civil use only. For military use, no certification or operational limitations apply.

9.3.4 SERVICE LIFE OF CRITICAL PARTS

The Astero is operated purely as on-condition and has no hard-time or soft-time components or parts. The aircraft does not have a dedicated maintenance programme as seen on certified manned aircrafts. Inspections are performed as pre-flight and post-flight inspections, verifying structural integrity and system functionality.

9.3.5 EXPECTED SCOPE OF IMPLEMENTING THE DIGITAL TWIN CONCEPT

The expected scope of implementing the DT is to provide a fully functional visually accessible real-time data platform to monitor the structural loading of the Astero, enabling analysis of structural performance and calculation of remaining useful life. Ideally, this shall include the wing skins, wing shear web, fuselage and bulkhead frames.

9.3.6 OPERATIONAL AND ENVIRONMENTAL CONDITIONS FOR THE IOT SKIN

The IoT skin for the wings will be mounted in or on carbon or glass fibre materials. We envision that the skin will most likely be molded into the structure in the production process, allowing the sensing skin to be an integral part of the wing skin design.

Table 9 Operational Conditions for the IoT skin on the Astero

Parameter	Value	
	Minimum	Maximum
Temperature [degC]	-10	35
Acceleration [m/s^2]	0	TBD
Environmental influence	Continental climate conditions, occurrence of light rain and moisture	
Typical duration of flight [min]	10	>120
Weight of the whole setup [g]		400
Max dimensions whole setup [mm]	100*120*105	

The installation of hardware in the Astero is restricted to the dimensions of the payload bay. The payload bay usually houses the advanced camera equipment carried by the Astero. It is not foreseen that the camera equipment requires to be installed for AVATAR flights, thus allowing the payload bay to house the equipment required for the AVATAR project.

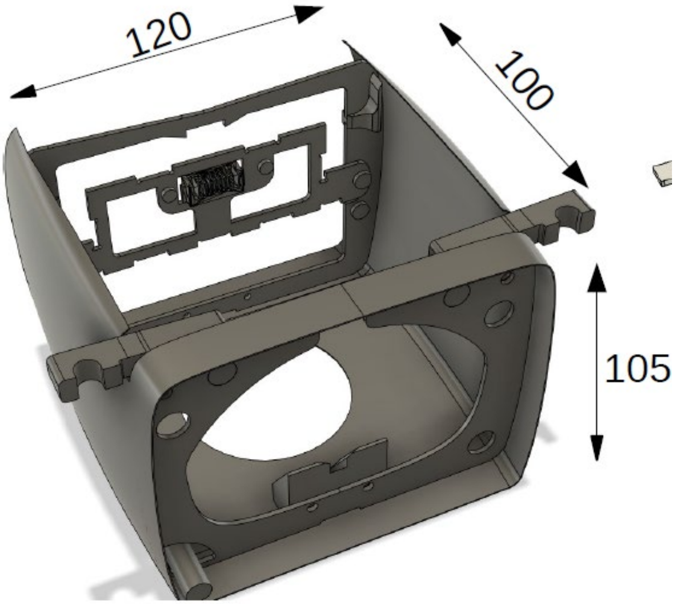

Figure 14 ASTERO Payload Bay Dimensions

Please note that all equipment required for being on board the Astero shall be integrated into the Payload Bay area. It is therefore required that all sensor equipment, processing equipment, and communication equipment (other than already installed equipment) shall be integrated. It is highly recommended that the integration be performed diligently, and selection of equipment takes the sizing of the payload bay into account in order to ensure compatibility and accessibility.

9.3.7 SUITABLE SENSOR LOCATIONS

The suitable sensor locations on the Astero are deemed to be in the upper and lower wing skins for the placement of strain gauges and thermistors. For accelerometers, the most suitable location will be the payload bay as close to the centre of gravity as possible.

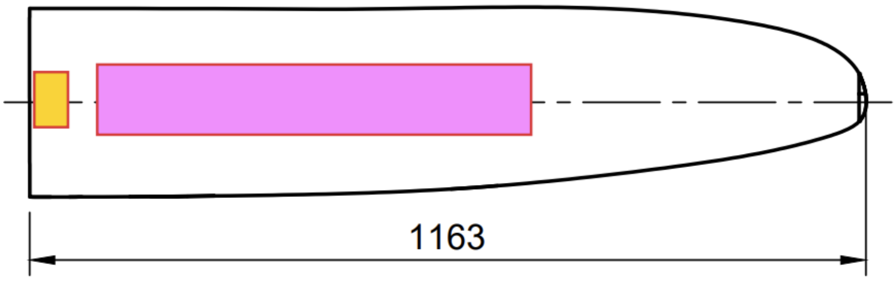

Figure 15 ASTERO Suitable Sensor Locations (wings)

9.3.8 SENSOR ACCESSIBILITY

The sensors in the wings will most likely be moulded into the construction, alternatively glued to the inner-most layer of each wing skin. Either way, the sensors will not be accessible after construction of the wing has been completed.

Sensors located in the payload bay are readily accessible when the wings are not installed. Placement of the sensors shall be taken into account when the mechanical integration in the payload bay is performed.

10 ASSESSMENT CRITERIA FOR THE PDM PLATFORM

AVATAR's technological and methodological advancements will undergo a comprehensive series of laboratory tests, ranging from simple coupons to more complex components representative of the airframe structures, under simulated operational environmental conditions relevant to the two demonstrators. These validations cover diverse aspects: i) evaluating monitoring during service operations, necessitating multiple sensors and varied acquisition systems; ii) ensuring seamless communication among IoT sensors situated on different air vehicle components, connecting with a central system and the cloud for real-time diagnostics; iii) implementing operational mechanisms to coordinate diverse sensing functions while achieving energy-efficient operation; iv) predicting integrity and optimizing the safe lifespan through multi-physics, multi-system simulations, incorporating uncertainties such as material variations, model parameters, environmental conditions, and loads; v) expanding Structural Health Monitoring (SHM) principles to real-time, in-service assessment based on data collected during flight. Additionally, the diagnosis and prognosis of air vehicles must align with performance evaluations and tangible actions (maintenance and repair). Detailed descriptions of further validation tests on the three demonstrators will be outlined in deliverable D1.2 and subsequent deliverables associated with these work packages.

In AVATAR, effective data communication plays a crucial role, especially in advancing predictive maintenance. The focus lies on collecting and communicating aircraft operational data, necessitating both onboard and Aircraft to Ground communication. The process involves employing Edge and Cloud infrastructure for data storage and (pre-)processing at the aircraft or/and Cloud levels. The platform's assessment hinges on data quality, aiming to minimize the transmitted data volume to the cloud during the pre-processing step. This is facilitated through a data fusion mechanism that manages heterogeneous, multi-scale, and multi-sensor data samples. Evaluating the platform also involves assessing the extraction of relevant features from the fused data to capture higher-level information, such as moving averages or frequency content. Additionally, the integration of dashboards is vital for the digital twin, focusing on presenting data to end users in an interpretable and actionable manner. The platform's assessment in this context considers the quality of displayed data, originating from both IoT sensors within the aircraft and prediction data generated by surrogate models using machine learning algorithms for diagnosis and prognosis.

11 CONCLUSION

Taking the above into account, the main points for creating a Digital Twin for Predictive Maintenance through Structural Health Monitoring becomes the adaptation of novel technology in order to gain useful insight in the behaviour of aircraft structures through the gathering of data, analysis of data and presentation of data for the RUL in the DT platform.

The gathering of data is dependent on the novel sensor technology having the capability to detect loads and temperatures in the required domains of frequency. The analysis of data is dependent on the ability of the system to store and communicate the data (including size of data and content) effectively and consistently.

The analysis of data is dependent on the storage, availability, analysability, and presentation of data in a manner that can create the foundation for calculation and presentation of RUL as a tool for evaluation of maintenance activities.

The previous sections define the requirements and the domains of expertise with which the partner institutions will work within the AVATAR project. A seamless integration of the experience in the consortium during processing of new findings and challenges should help the team to reach the project goal.

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