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Wireless data transfer system architecture for predictive maintenance of aircraft landing gear

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In this paper, we describe the data transfer techniques used so far for landing gear and other critical aircraft systems predictive maintenance applications, as well as the available wireless data transfer techniques. Moreover, the architecture of a wireless transfer system for sending aircraft's landing gear sensory data to a ground station is described, proposing the main guidelines in terms of middleware development and data security and fidelity.

I. Introduction

The current status of the maintenance of the landing gear system has mostly been preventive or corrective/on-condition maintenance, involving actions that are taken on specific intervals, that are calculated in regards to specific criteria or in case of unexpected events, like hard landings, after the inspections that follow them. The criteria can be the number of flight hours and landings, as well as, statistical data from past operations and engineering experience. The fatigue or failure of the components though can be affected by environmental factors and the age of the equipment, therefore the maintenance intervals are usually calculated conservatively, leading to redundant activities and increased cost and overhaul time. [1] The usage of health monitoring systems on the subcomponents of the landing gear can give crucial information regarding their state, that can be used in predictive maintenance algorithms, that together with expert knowledge can be used to reduce unscheduled repair and maintenance time and costs and increase the aircrafts' availability. [2]

The aim of this research effort is to develop a data management and transmission architecture, dealing with problems like wireless transmission security and data fidelity, while at the same time identifying the advantages and limitations of different wireless data transfer methods and their performance on airport gates or hangar settings. The proposed architecture should be able to transfer wireless data collected from sensors on the landing gear of commercial aircraft and then transmit them in a secure and reliable way to a ground station while the aircraft is on the gate/taxiing or in a hangar environment, for further processing.

II. Data transfer techniques

There are not a lot of topologies found in the literature regarding landing gear sensory data transfer from an aircraft base station to a ground station, for predictive maintenance purposes. Most of the approaches found concern small-scale

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projects with few prerequisites on data transfer security and fidelity, as well as smaller amounts of data. Moreover, a lot of predictive maintenance techniques use historical sensory datasets. On the other side, while there are some commercial systems for data transfer for predictive maintenance purposes, most of the techniques found, concern real-time aircraft engines' sensory data transfer using often satellite communications. In figure 1, we can see the various data transfer topologies.

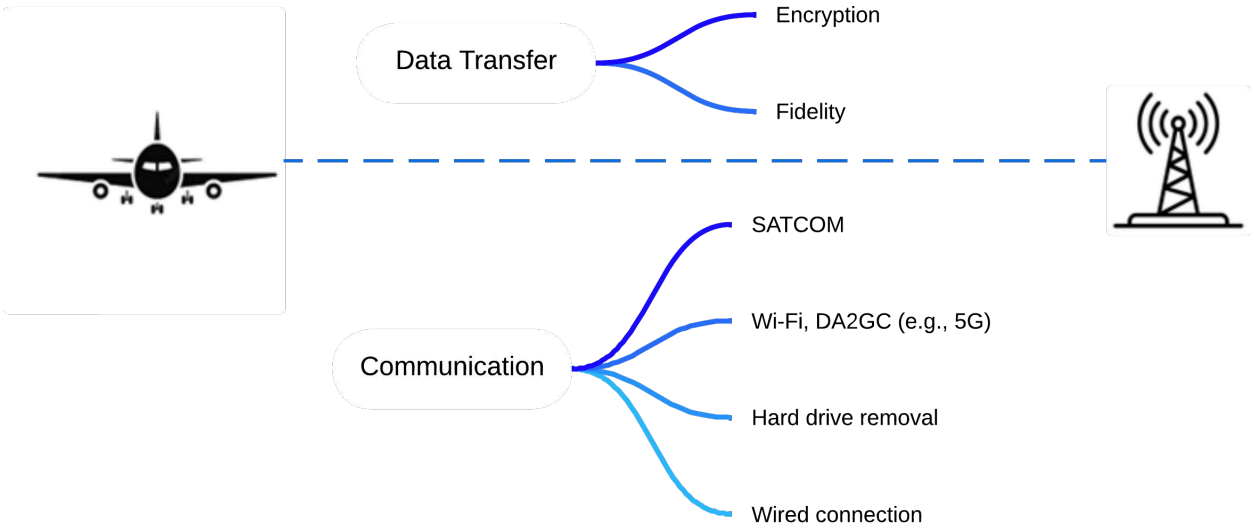

Fig. 1 Data transfer topologies

A. Landing gear systems

Usually, the remaining useful life of the landing gear systems is underestimated, due to generalizing the impact cycle to all landing gear systems, as well as, because of ground inspections when the pilots are uncertain about the landing gear's condition after performing hard landings [3]. Therefore, using data generated from sensors on the landing gear systems, together with the usage of predictive maintenance models, can help estimate correctly the fatigue and the condition of the systems, decreasing unnecessary inspections and thus decreasing costs and increasing the remaining useful life of the components. More specifically, the usage of health monitoring systems on landing gear can help discover hard landings that the crew was not able to realise, but still caused excessive fatigue to the landing systems, as well as, reduce costs by not implementing redundant inspection after a suspected hard landing, in case the sensors have measured normal loads on the landing gear systems. [4]

In [5] the authors use pressure data from sensors to explore the role of hard landings and improve predictive maintenance by informing the pilot about the landing outcome, in a lightweight aircraft. The data from the sensors are sent to the main board in the cockpit wirelessly using Zigbee modules and then the data will be sent to a smartphone with Bluetooth 2.0 protocol. In [6] the authors propose a scheme that studies the acceleration and pressure of shock absorbers of the landing gear of lightweight aircraft, in order to calculate the mass and centre of gravity measurements. The data gathered from the sensors are transmitted to the cockpit using Bluetooth protocol and are visualised by a Java interface. In [7] a framework for detecting structural damages of the landing gear system is proposed. The Ethernet method is used for the data transfer to the ground station, but only ground trials were carried out. Also, other methods like [8, 9] do not have a connection to a specific ground station to send the sensors' data, but instead use historical sensory data, that are at a later stage used from the predictive maintenance algorithms. As we can see most of the approaches mentioned above are referring to small scale projects, using Bluetooth, which provides lower speeds than 5G and Wi-Fi6.

B. Engines and other systems

For aircraft engines and other critical systems usually air to ground communication, which is frequently real-time or near real-time, is used for the data transfer of predictive maintenance data. This type of communication can be either direct air-to-ground communication (DA2GC) or satellite communication (SATCOM) [10].

In [11] a real-time air-to-ground communication system combining ultrahigh-frequency communication link, 4G cellular mobile communication link, and satellite communication link was proposed for engine health management. For the ground-to-ground communication between the different processing departments that the data should be sent, the user datagram protocol (UDP) WiFi method was used that supports one-to-many and many-to-many interactive communication. In [12] the authors propose a system for wireless transfer of data from aircraft sensors to a ground station. They use a multi-path resistant based multicarrier COFDM waveform at 2.4GHz, together with specific techniques enhancing data fidelity and encryption. The transfer can be successful while the aircraft is on the ground or inside a ratio of 10km, achieving zero packet loss, while the ground station can receive data from multiple aircrafts. Most of the methods found regarding predictive maintenance of engines are using the Commercial Modular Aero-Propulsion System Simulation (C-MAPSS), which is a transient simulation of a large commercial turbofan jet engine, with a realistic engine control system developed by NASA and do not implement real-time air to ground communication. Nevertheless, some commercially available data transfer solutions for predictive maintenance include PROGNOS from AirFrance—MRO Lab, Airbus Real Time Health Monitoring Service (AiRTHM), AnalytX from Boeing and Ascentia from Collins Aerospace, among others. [13]

C. Proposed data transfer methods characteristics

In the case of landing gear systems, that are only used in the takeoff and landing phases, in-flight monitoring and in-flight transfer of sensory data are not necessary, therefore, the data transfer can be implemented with ground-to-ground communication only.

For the ground-to-ground communication method, the simplest method is the manual removal from the airplane's base station of the hard disk or flash memory where the data are stored. This method is simple and low cost, having potentially fewer risks on data fidelity and security, but is difficult to implement on a frequent basis, or out of MRO facilities. Other methods, include using wireless transfer, which provides the opportunity for frequent automatic data transfer, without occupying maintenance personnel. The wireless transfer can be either Wi-Fi or 4G/5G using already-built terrestrial communication infrastructure. In these two methods, the mmWave counterparts are included as well, which offer higher speeds with usually smaller range. Wi-Fi has been proposed in the past for In-Flight Entertainment (IFE) data uploading [14]

Technology	Spectrum	Peak Data Rate	Range	Operator	Limitations
Wi-Fi 6	Shared	9.6 Gb/s (802.11ax)	45–150 m	Airport / Local Operator	Number of users
Wi-Fi	Shared	6.9 Gb/s (802.11ac)	50 m	Airport / Local Operator	Number of users
AeroMACS	Dedicated	50 Mb/s	Several kilometers	Airport / Local Operator	Number of users / Base Station
4G (Cat.21)	Dedicated	1.4 / 0.3 Gb/s (DL/UL)	Several kilometers	Cellular Operator	Number of users / Base Station
5G	Dedicated	20 / 10 Gb/s (DL/UL)	Several kilometers	Cellular Operator	Number of users / Base Station
5G mmWave	Dedicated	20 / 10 Gb/s (DL/UL)	500 m	Cellular Operator	Line of sight

Table 1 Characteristics of Different Wireless Technologies for Aircraft Data Transfer

5G operates in both licensed and unlicensed bands, while Wi-Fi operates in unlicensed bands and common

frequencies of 5G include 600 MHz, 800 MHz or the millimeter wave paradigm that operates between 30 GHz and 300 GHz. Wi-Fi operates in 2.4 GHz and 5 GHz, while Wi-Fi6E operates at 6 GHz. Both protocols provide various built-in authentication and security algorithms like WPA3 based on Simultaneous Authentication of Equals (SAE) for the Wi-Fi6 case. 5G incorporates authentication and key agreement (AKA) protocol derivatives and SIM authentication, providing one extra layer of security compared to Wi-Fi. Moreover, beamforming is another characteristic of communication security in 5G systems, constructing highly directional (thus secret) channels between a transmitter and the intended receiver [15]. In terms of speed, both approaches provide sufficient download speeds for this application, with 5G reaching theoretically 20 Gbps and Wi-Fi6 reaching 10 Gbps. As for the range, 5G can have a range of some kilometres while Wi-Fi6 has a range of 45-150 meters outdoors. In table 1 we can see most of the wireless data transfer methods, as well as, some of their important characteristics [16].

III. Wireless data transfer architecture

As we can see in Figure 2, the overall wireless data transfer architecture is constituted by the data acquisition unit that is connected to the sensors, which can be strain gauges of the landing gear in our case. Then the data acquisition unit is connected to the aircraft base station computing unit, where also simulated data can be loaded for experimental purposes. This unit integrates all the communication equipment, like the Wi-Fi and 5G cards, as well as the antennas needed for achieving the required signal strength. This unit implements the communication protocols needed and sends the data to the ground station, where the data can be accessed or uploaded to the cloud.

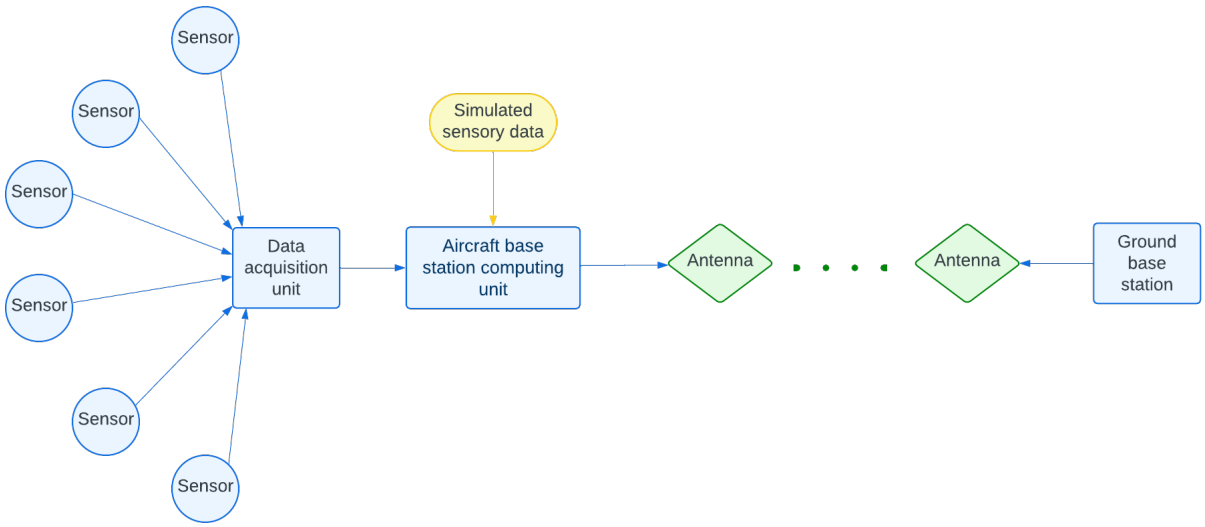

Fig. 2 Wireless data transfer architecture

A. Data acquisition and computing unit

The Data acquisition unit on the aircraft side (see Figure 3) is the hardware that implements the connection with the strain gauge sensors of the landing gear and the aircraft base station computing unit. The Data acquisition unit on the aircraft side is constituted by the microcontroller ADC Interface unit that has a Renesas RA4M1 (Arm® Cortex®-M4) processor with up to 14-bit resolution. The microcontroller is equipped with a real-time clock since we need time-stamped data and is connected to the aircraft base station computing unit equipped with an ASUS ROG STRIX B760-I Mini-ITX motherboard and an Intel Core i7-14700K processor, that finishes the data processing and implements the wireless transfer. The microcontroller is connected to 3 pairs of strain gauges with Wheatstone bridges and amplifiers, achieving effective data transfer.

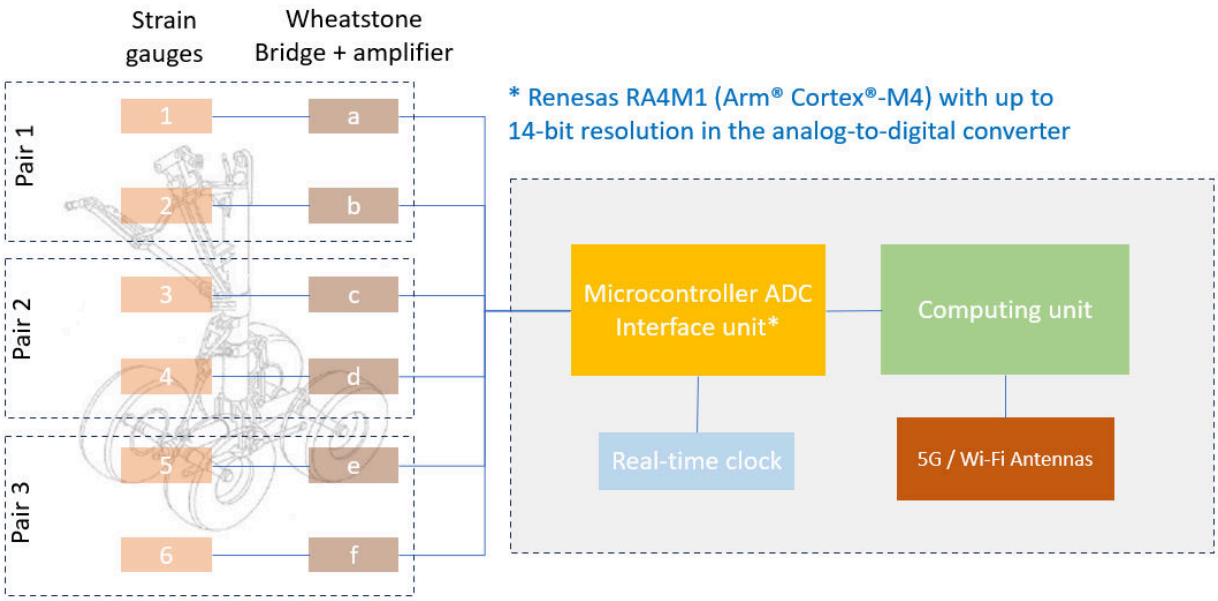

Fig. 3 Data acquisition unit on the aircraft side architecture

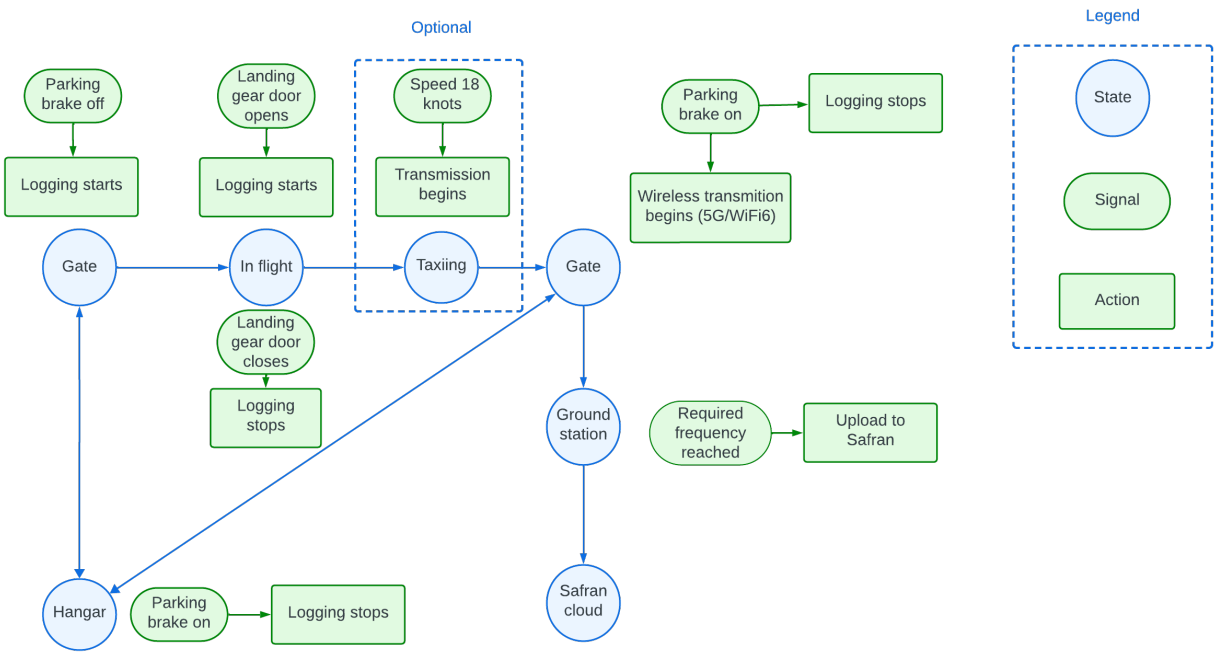

Fig. 4 Data logging and transfer decision architecture

B. Data logging and transfer decision architecture

There are various signals that need to be used to control the data logging and data transfer start and stop actions (see Figure 4). We can see that the state of the aircraft is, represented by a circle, while the oval shape represents the signal needed to be issued and the rectangular the action that follows the implementation of the specific signal.

When the aircraft is at a gate, and the parking brake is not activated, the logging starts, and the aircraft can go to a hangar or another parking spot, where the logging of the data stops again when the parking brake is activated again or to proceed to the take-off procedure. While the aircraft is in the air, logging stops when the landing gear door closes and

starts again when the landing gear door opens again during the approach to the airport phase. After landing, the aircraft can begin the transmission of the data when the speed reaches 18 knots since this indicates the taxiing phase (but this could only be applicable to the 5G wireless transfer method due to the range limitations of the Wi-Fi method). When arriving at the gate and the parking brake is activated, logging stops again, and the wireless transmission of the data begins. The data are received from the ground station and are uploaded to the cloud with a predetermined frequency.

C. Middleware architecture

The middleware, which is the software architecture that connects the various subsystems that implement the data transfer, should also follow some specific guidelines regarding the data collected. Some of the guidelines are included in ISO 13374-1:2003, which establishes general guidelines for software specifications related to data processing, communication, and presentation of machine condition monitoring and diagnostic information. Moreover, the fidelity of the data, as well as their security, both play a significant role, especially in the wireless methods [7, 17]. Therefore, good practice is the middleware to be built using the DDS (Data Distribution Service) specification, which is a protocol defined by the Object Management Group (OMG). The DDS describes a Data-Centric Publish-Subscribe (DCPS) model for distributed application communication and integration. This specification defines both the Application Interfaces (APIs) and the Communication Semantics (behaviour and quality of service) that enable the efficient delivery of information from information producers to match consumers [18]. In this work, we use one commercial DDS solution, which is a middleware implementation that provides both the OMG DDS 1.4 and the OMG RTPS 2.2 interoperable wire-protocol standards.

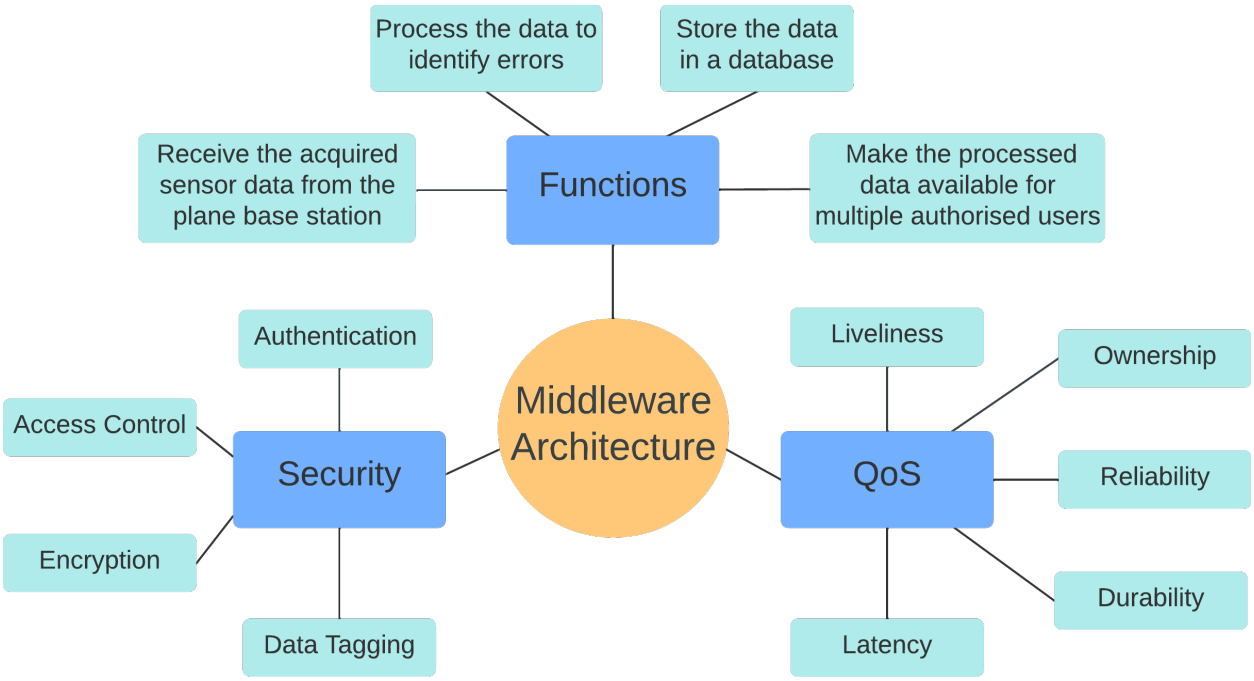

Fig. 5 Middleware architecture

As shown in Figure 5 the middleware's primary functions are to receive the acquired sensor data from the plane base station and store the data in a database. Also, to process the data in order to identify errors in the transmission procedure and make the processed data available for multiple authorised users [19].

For better compliance to the above goals and to ensure data security and fidelity, the middleware should also comply with some specific security and Quality of Service (QoS) criteria. The main security functions include authentication by the users using a trusted certificate authority (CA), as well as access control. Moreover, the encryption of the transmitted data should be implemented and data tagging (the addition of security labels to the data) can enhance access control security. The database where the data will be stored should be accessed only by authorized users, and the sender or receiver should be able to prove their identity through authentication, and stored information should be amended only by authorised users [19]. As for the QoS, many parameters can be taken into consideration with Reliability and Durability

being some of the most important. Data should be delivered to all subscribers without errors, and subscribers should be ensured that they get all the data that was sent, regardless of when it was sent. Moreover, Ownership is important since it can help users build systems with redundant elements to prevent component or application failures. Furthermore, Latency and Liveliness play an important role among the various QoS parameters too.

D. Validation and future plans

In order to validate the correct function of the proposed architecture, the data acquisition unit and the aircraft base station will be placed inside the landing gear bay of the B737 aircraft that exists in the Hangar Laboratory facilities in the Digital Aviation Research and Technology Centre (DARTeC) at Cranfield university. We will measure the data transfer under various conditions and the impact of the large metallic bodies of the aircraft and an airport gate, and also compare the performance between 5G and WiFi6/6E. Furthermore, WiFi7 will also be tested as it will start to be more broadly available, as well as 4G since this is the cellular solution used in cases where 5G signal is unavailable. In the case of wireless transfer, base airport infrastructure improvements could be necessary, like the introduction of more WiFi extenders or mobile antennas, especially in the case of providing the service to a fleet of aircraft.

IV. Conclusion

Consequently, we see that for landing systems, sensory data transfer ground-to-ground communication is preferred over air-to-ground communication used in other critical systems. We propose the main components of a wireless data transfer architecture and highlight the middleware best practices. Moreover, the usage of the most common wireless data transfer methods in aircraft data transfer remains an open field of research, especially in terms of data integrity, despite their built-in capabilities in security and data fidelity.

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Project: OLLGA (Optimised Life for Landing Gear Assemblies), with Safran Landing Systems UK Ltd as Industrial Lead.

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