Wireless Sensor Network for Structural Health Monitoring in Airplanes

Ahmad Baksh,

SATM School of Aerospace, Transport and Manufacturing.

Cranfield University, United Kingdom

Email: ahmad.baksh@cranfield.ac.uk

Abstract

The aim of this paper was to provide a brief exploratory qualitative review of research on wireless sensor networks for structural health monitoring in airplanes. Search using Google Scholar yielded 20 usable papers published till 2016. Wireless sensor networks do away the need for the costly, cumbersome and difficult to manage wired monitors and do away with the need for regular maintenance schedules to increase the availability of the aircraft for the intended services. Thus, it is cost-effective. Crucial factors are the need for efficient operation at low energy levels and energy harvesting systems. Many methods, including piezoelectric materials have been found promising. Much research has been done on detection of fatigue and damage to aircraft structures. Real time monitoring while in flight may save many lives in time. Much more research is needed on this aspect.

Keywords: Wireless Sensor Network, Structural Health, Airplanes, Review

Introduction

Structural health monitoring used to be done to assess the integrity of structures of buildings, bridges, dams and aerospace structures. Researches in this field focus on the development of systems and technologies. Wired data on variables such as vibrations from various locations of the structures are analysed. Changes in patterns of such vibrations could be due to the influence of some external natural or human activities like movement of heavy vehicles, major building activities nearby, earthquakes etc. However, installation of wires are costly and time-consuming. Use of wireless sensor networks assumes importance here as a cost-effective, modern and convenient technology. It has been shown by research that such wireless sensor networks (WSN) are very useful to track the structural health of airplanes also. This paper undertakes an exploratory, brief and qualitative review of the works done in this direction.

Method

Google Scholar was used as the search engine using appropriate search terms specifying WSN for structural health monitoring of airplanes. The search was limited to the period till 2016. The search yielded 20 usable papers. These are discussed under different sections below.

Results

WSN general trends

In their paper, Notay and Safdar (2011) described a WSN-based structural health monitoring of airplane in which sensors were placed at optimum locations in the plane. OPNET simulation validated the efficient functioning of the system.

Use of autonomous sensor nodes serve as key elements of WSN for self-sufficient operations without serious maintenance problems and avoiding complex wiring to supply power and communication needs, as was noted by Becker, Kluge, Schalk, and Tiplady (2009).

The technological aspects of developing a smart networkable wireless sensor to monitor the aircraft engine health was discussed by Nickerson and Lally (2001). Intelligent component health monitoring concept is used in many industrial applications and is adapted here. In the case of aircraft, the device needs to be environmentally hardened. Some additional self-calibration and test functions need to be incorporated. Transducer technologies need to be integrated. An engine sensor network based on intelligent component health monitoring needs to be integrated. All these adaptations need to be tested in real time aircraft environments.

Usefulness of SHM for design and structural monitoring purposes was discussed by Boller and Buderath (2007). The balance between gain through lighter weight versus loss resulting from enhanced inspection effort has been positive with lower direct operating cost (DOC). To minimise DOC, either more controllable damage should be permissible or improve and automate the inspection to reduce inspection cost or do both. SHM using wireless sensors offer an attractive solution to this problem. While discussing fatigue design and evaluation, the authors presented the fatigue-vulnerable areas of an ageing Airbus A300, reproduced in Fig 6. Only six fatigue-susceptible areas have been identified. Accidents had facilitated identification of weaknesses in measuring, monitoring and actioning on fatigue in aircrafts, which had caused heavy loss of human life. Future accidents may throw up more vulnerable spots.

While discussing many applications of wireless sensor technology, Yedavalli and Belapurkar (2011) also discussed structural health monitoring (SHM). Use of composite materials for aircraft structures has increased tremendously and is continuing. This necessitates the development of novel methods for aircraft structural health monitoring. Delamination of layers is the first symptom of failures of composite structures. Cracks develop in metal structures. These cracks grow over time leading to failures. Visual inspection is not a reliable method for failure detection in both cases. Traditionally, a vibration analysis-based failure detection method had been used. The cost of the current scheduled aircraft structure maintenance methods has been high. Use of wireless sensor networks is relevant from this point of view.

A new multi-response-based WSN was proposed by Yuan, Ren, Qiu, and Mei (2016). The aim was to achieve large-scale impact monitoring with significantly reduced the weight and complexity of the monitoring system. The multi-response-based global impact localization method of this system could unite multiple leaf nodes to solve the problems of localization confliction and mid-region localization. The model was evaluated for validation.

Specific technologies

Ultrasonic monitoring

In 2007, Zhao, et al. (2007) reported the successful testing of two wireless ultrasonic structural health monitoring of aircraft wings. In the first approach, passive transducers and an antenna were embedded inside the structure while the energy was coupled to the transducer with an external transmitting antenna. The transmitting and receiving devices needed to be in close to each other due to their reactive coupling nature. A diagram of this set up given by the authors is reproduced in Fig 1. However, remote integrity monitoring of aircraft wings is not possible with this system but can be used for in-aircraft monitoring.

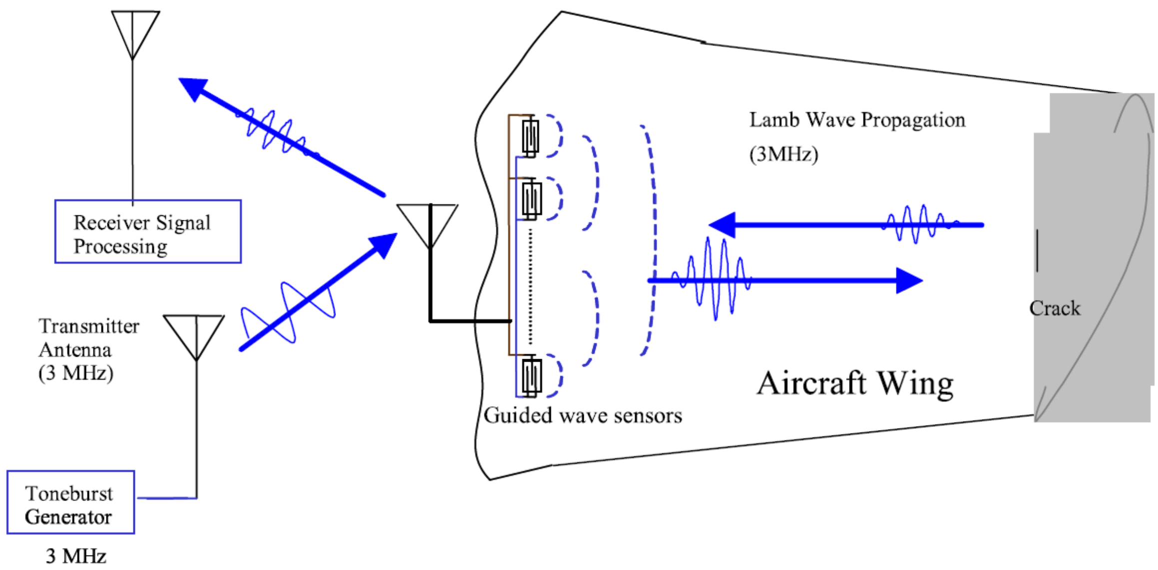

Figure 1: A system of SHM wireless direct analog RF coupling sensor network for structural health monitoring proposed by Zhao, et al. (2007).

In the second approach, both the transducer network and the data acquisition device are embedded into one structure. The data can be downloaded wirelessly using a radio with good signal quality, range, and unaffected by any interference. Delivery of power to the module is achieved wirelessly at X-band with a rectenna array attached to the aircraft body, eliminating the need for batteries. In the experiment, this fully embedded system with a PZT sensor panel on the wing produced accurate detection of defect and its location. A diagram of this system given by the authors is reproduced in Fig 2.

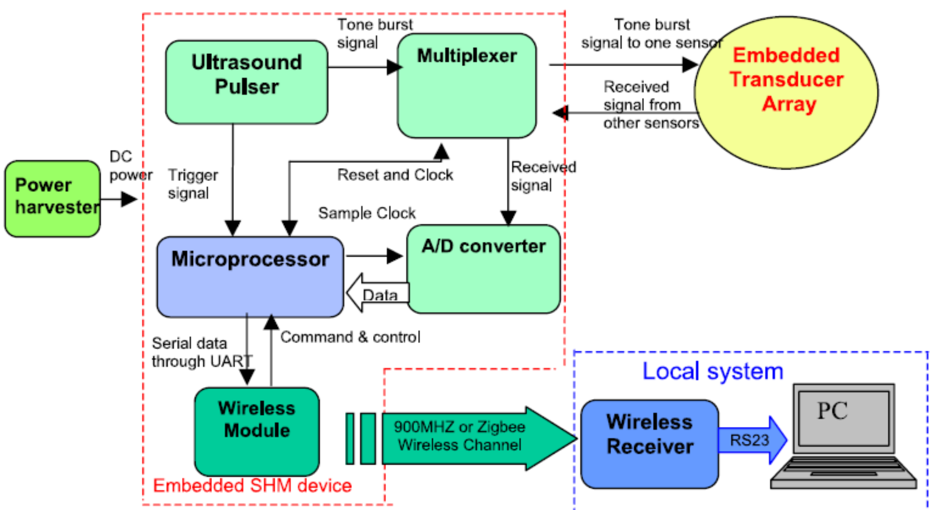

Figure 2: A fully embedded ultrasonic structural health monitoring system proposed by Zhao, et al. (2007).

WSN embedded in the structures

Yedavalli and Belapurkar (2011) pointed out that WSN can be embedded into the composite structure. This can harvest the vibration energy and transmit the real-time data to the central health monitoring unit. These sensors can be used to monitor the internal parameters like cracks, strain as well as external parameters like temperature, load, etc. The number of sensors as well as their life can be increased by using WSN, which is powered by energy harvesting methods. Also, the availability of real-time data will enable the use of condition-based maintenance rather than the costly scheduled maintenance, thereby preventing catastrophic failure of aircraft structures. Microelectromechanical systems can be used for implementation of WSN based aircraft structural health monitoring. But further research needs to be done on optimum energy harvesting and power management methods for these sensors. Effect of air flow is an important factor if sensors are attached to the top of the aircraft.

Energy harvesting

Combining energy harvesting with WSN can enhance the ability to monitor and maintain the health of critical structures of aircrafts. Noting this, Arms, et al. (2009) reported on the development of an integrated SHM for naval aircrafts. Data from both wireless and hard-wired sensors were integrated in a versatile fully-programmable system. An embedded Global Positioning System (GPS) was used for providing data on the position, velocity and precise timing. Multiple sampling rates with time stamping were aggregated within a single scalable database located in the base station. The base station also provided tracking and tracing capability to synchronise sensor nodes with embedded precision. Synchronisation to an accuracy of milliseconds and its sub-levels is also possible. Both burst (oversampling) and periodic sampling are possible.

The ability of piezoelectric materials to convert strain energy into stored energy makes it suitable to measure, record, transmit strain and load information. Arms, Townsend, Churchill, Moon, and Phan (2006) reported development of a low energy model for helicopter. The system was found to consumed lower energy than what was consumed. Thus, almost perpetual operation of load and strain monitoring sensors was possible.

A self-powered WSN system based on piezoelectric energy harvesting was proposed for SHM of aircrafts by Lu, Savvaris, Tsourdos, and Bevilacqua (2016). The light-weight prototype could be easily implemented and integrated into an aircraft environment. Excess energy could be stored in capacitors. The applicability of the system was validated through experiments.

The design and prototype of a self-powered sensor node was proposed by Somov, Chew, Ruan, Li, and Zhu 2016) for the aircraft structural health monitoring. The sensor node was powered by the ambient vibrations generated by the aircraft wings. Sensing devices performed the condition monitoring of structures and systems comprehensively and measured environmental parameters like ambient temperature and ionizing radiation levels to help operators in assessing the aircraft status at every stage of its mission. With the wireless communication the sensor nodes could be networked with no need for wiring, leading to not adding weight to on board.

Security applications

Regulatory institutions know that security requirements for network-enabled airplanes must be fully identified. In their paper, Sampigethaya, et al. (2007) focused on wireless airplane health monitoring and management systems (AHMMS) in relation to a security framework to identify threats and system requirements to mitigate these threats. The challenges and problems in enabling secure use of wireless sensor networks for health monitoring and control of commercial airplanes were also discussed. The authors presented the model of the system, reproduced in Fig 3.

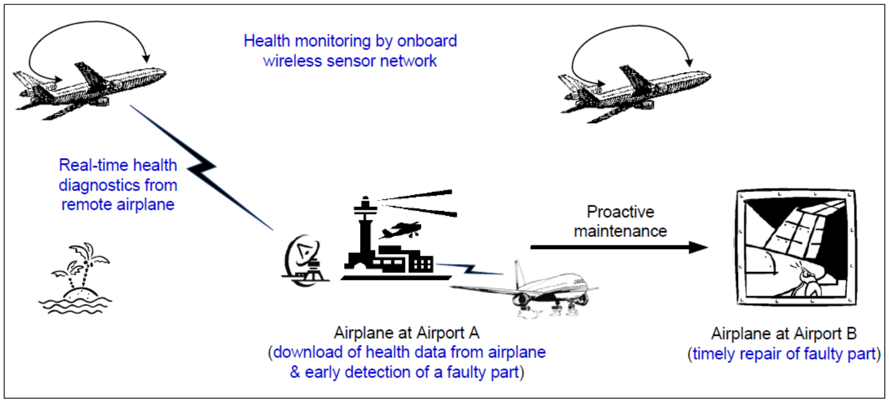

Figure 3: Model of the airplane health monitoring and management system (Sampigethaya, et al., 2007)

Health monitoring and management systems are considered as key enablers of next generation of airplanes like Boeing 787 or Airbus A380 models. The output of sensors provide continuous feedback to onboard units and to airports. Onboard units can use the data for real time operations and ground controllers can take proactive steps. However, introduction of e-enablers can increase the vulnerabilities of the airplane security systems to open networks. A modified AHMMS was proposed by the authors to get around this problem, which is reproduced in Fig 4. In this system, the thick arrows indicate wired and trusted communication links. The thin arrows represent wireless untrusted communication links. The authors discussed the methods of dealing with multiple types of threats.

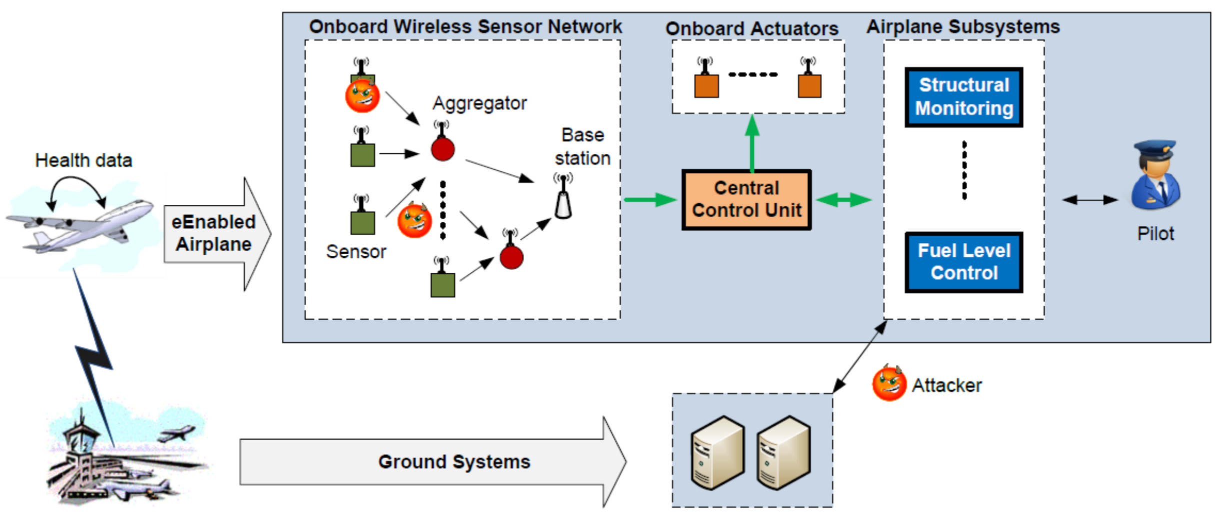

Figure 4: The AHMMS model proposed by to solve security problems in using open networks (Sampigethaya, et al., 2007)

Aircraft fatigue, impact and damage

Airplane structures may suffer fatigue and static problems. Wired technologies are inefficient and costly. Hence, Wu, et al. (2009) developed and validated a WSN-bases system for aircraft strength testing (AST). The system given by the authors is reproduced in Fig 5.

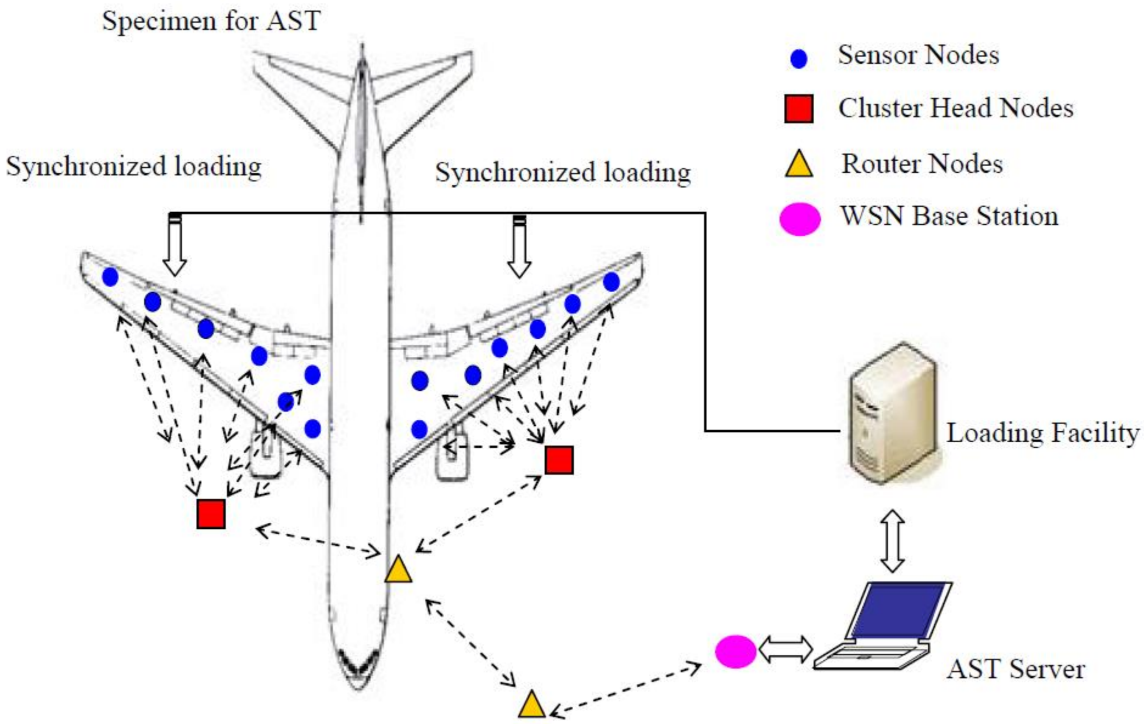

Figure 5: The WSN-based system for airplane strength testing (Wu, et al., 2009)

Use of thermal gradients for efficient energy harvesting for various uses of sensors was proposed and models validated by Bailly, et al. (2008) and by Samson, Otterpohl, Kluge, Schmid, and Becke (2010).

There is good scope for using piezoelectric wafer active sensors on aging aircraft structures to monitor the onset and progress of structural damage such as fatigue cracks and corrosion. This was point was reviewed by Giurgiutiu, Zagrai, and Bao (2002). Two methods were discussed: elastic wave propagation for detection of far-field damage and the Electro-Mechanical (E/M) impedance for detection of near-field damage. Damage detection algorithms used in these two methods are different. An ultra-low power network of WSN application for testing and assessment of damage due to corrosion was developed and validated by Demo, Friedersdorf, Andrews, and Putic (2012).

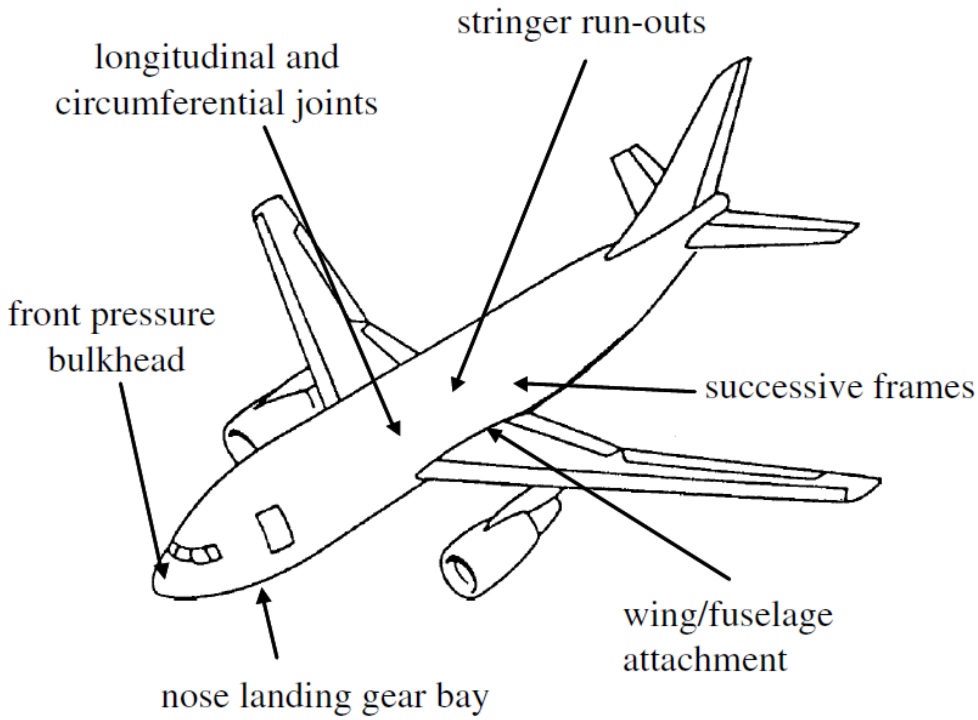

Figure 6: Fatigue-susceptible areas of an ageing Airbus A300 (Boller & Buderath, 2007)

Fibre optic sensors

SHM of composite aircraft structures, while in service, has a dominant role in the assessment of their performance and integrity. In recent years, Fibre Optic Sensors (FOS) has the potential to facilitate real-time in-situ monitoring of these structures. FOS has numerous advantages including immunity to electromagnetic interference, small size, light weight, durability, and high bandwidth. These advantages enables use of a large number of sensors to operate in the same system with possible integration within the material. (Di Sante, 2015) reviewed research works on this aspect with respect to both the multi-point and distributed sensing techniques of FOS. Increased use of composite materials for aircraft parts is exemplified in two diagrammatic presentations, reproduced in Fig 7 on Boeing 787 and historically in Fig 8 on Airbus.

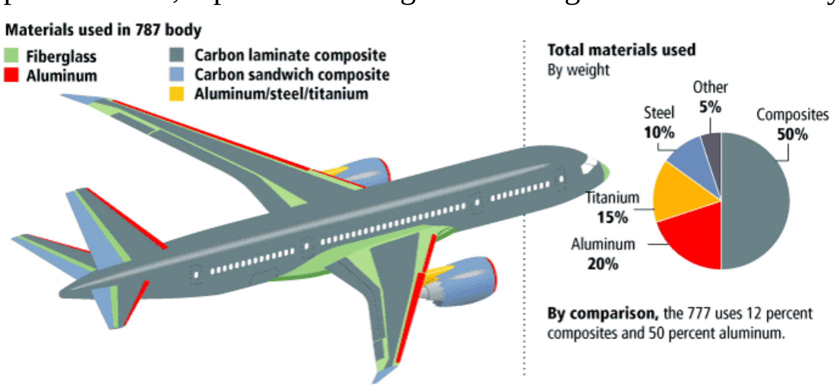

Figure 7: Materials used in Boeing 787 (Di Sante, 2015)

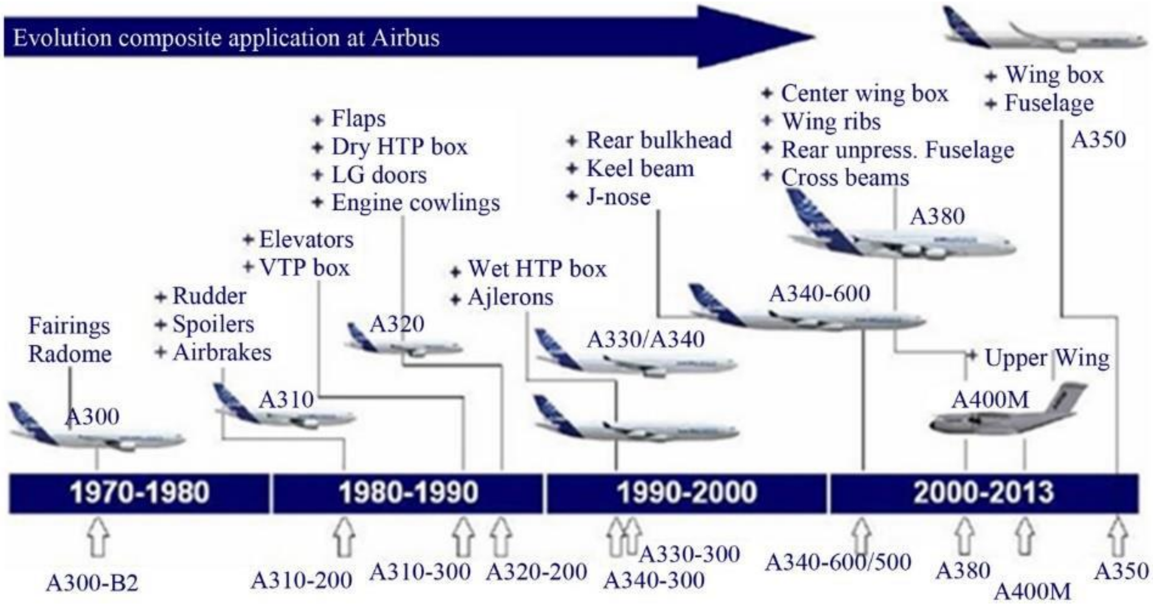

Figure 8: History of use of composite materials in Airbus over the years (Di Sante, 2015)

The impact of multiple external objects on composite structures is common. Such impacts may produce dents of various types and depth. The number of impacts and location are difficult to determine. Zhong, Yuan, and Qiu (2015) proposed a near-field 2D multiple signal classification (2D-MUSIC) method to solve the problem. The system can estimate parameters of different types of impacts without the need for signal separation. Results proved closeness between estimated and actual number of impacts. The method was successfully applied to an airplane fuel tank to prove its applicability to complex composite structures. One of the applications of fibre optics sensors, discussed by Di Sante (2015) was impact damage detection. Mainly damage due to bird hits, very common in flights, was discussed here. The likely areas of aircrafts susceptible to bird hits was diagrammatically presented by the author, reproduced in Fig 9.

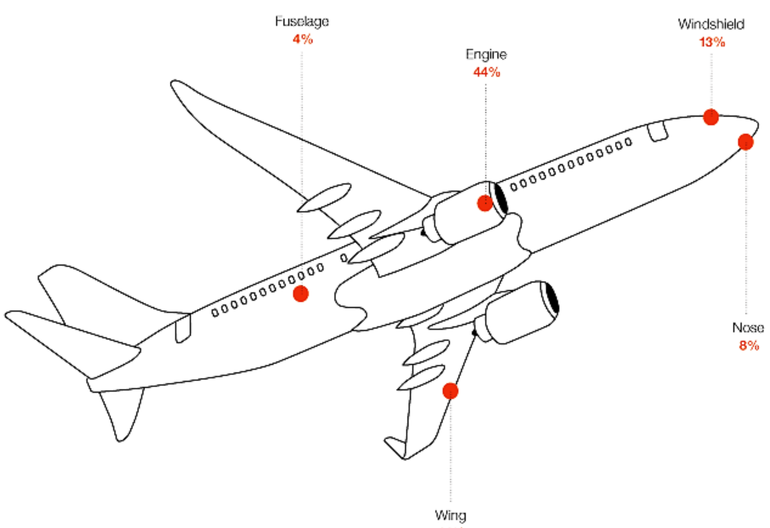

Figure 9: Likely bird hit areas of an aircraft (Di Sante, 2015).

Electromechanical impedance method has useful applications in various real time SHM applications. Instead of massive costly single channel impeders, an array of piezoelectric transducers can be placed over the area to be measured for incidence; location and extent of a damage. Current hardware solutions to measure the electromechanical impedance of multiplexed bonded transducers have limited data acquisition capabilities. Maruo, de Faria Giachero, Júnior, and Neto (2015) presented a hardware which does not have these problems. The prototype was successfully tested by simulation and real life aircrafts systems.

Conclusions

The compromise between increasing load of the aircraft for wired monitoring and regular maintenance schedule as a costly alternative, is well achieved when WSN is used integrating efficient low energy utilisation and harvesting. Other components like algorithms for various purposes are easily achieved once the system is determined. One of the main problems is detection of fatigue, damage or significant impacts like bird hits which can compromise air travel safety. Although a lot of progress has been made here, much kore needs to be done to strike at the root of these problems and insulate air travel against accidents.

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