Abstract: Aircraft industry has to meet a challenge of reducing operational and maintenance costs. One of the possible ways for reducing these costs is the introduction of wireless sensor networks (WSNs). WSNs are already finding a variety of applications for both safety-critical and non-safety-critical distributed systems. This paper deals with the application of WSNs for aircraft structural health monitoring. Special attention has been given to the use of Micro-Electro-Mechanical Systems (MEMS) as promising technology for implementation into WSNs. Some of the important technological challenges which have to be solved in near future are presented at the end of the paper.

Key words: wireless sensor networks, aircraft structural health monitoring, micro-electro-mechanical systems, condition-based maintenance, sensor node, energy harvesting.

1. INTRODUCTION

In the commercial and military aircraft there is a number of safety-critical and non-safety critical systems. These systems are based on wired connections and, therefore, they are complex and difficult to route. The Airbus A380, for instance, has over 300 miles of cables consisting of approximately 98,000 wires and 40,000 connectors. Cable routing is quite a complex task, as for example, the power cable and electrical signal cable should be physically separated to avoid electrical interference. Also, harsh environmental conditions impose physical restrictions on the use of a wire harness. Replacement of the current wire harness-based sensors with a wireless sensor network (WSN) can help to achieve the goal of increasing the number of sensors, as well as the system redundancy. It will also reduce the aircraft system weight and lead to improved fuel efficiency and reduced carbon emissions. Replacing the physical cabling by wireless connections also offers significant benefits regarding flexibility, interoperability, mass reduction and improved robustness. Use of WSN also enables reduction in direct costs and maintenance costs.

The base of structural health monitoring (SHM) is the ability to monitor structures using embedded or attached nondestructive evaluation sensors and to utilize the data in order to assess the state of the structure. SHM is a new and improved way to make a non-destructive evaluation with a minimum of manual intervention. It includes all monitoring aspects which are related to damages, loads and conditions, which have a direct influence on the structure. Knowing the integrity of in-service structures on a continuous real-time basis is a very important objective for manufacturers, end-users and maintenance teams. Structural health monitoring allows an optimal use of the structure, a minimized downtime, and the avoidance of catastrophic failures. Therefore, structural health monitoring drastically changes the work organization of maintenance services: by aiming to replace scheduled and periodic maintenance inspection with condition-based maintenance and by drastically minimizing the human involvement, and thus improving safety and reliability [1].

2. WIRELESS SENSOR NETWORKS TECHNOLOGY

Wireless network refers to any type of computer network which is not connected by cables. It is a method by which homes, telecommunications networks and business installations avoid the costly process of introducing cables into a building, or as a connection between various equipment locations. Wireless telecommunications networks are generally implemented and administered by using a transmission system called radio waves. AM radio, FM radio, satellite radio, satellite TV, satellite Internet access and broadcast TV are, in fact, wireless networks. Hence, the usage of wireless technology is very
convenient. We do not have to worry about running wires in tight places or obtaining low-voltage permits. Wireless sensor networks (WSNs) consist of spatially distributed autonomous sensors designed to monitor physical parameters or environmental conditions such as temperature, strain, pressure, vibration, sound, motion, pollutions, etc. Consequently, the sensors cooperatively pass their data through the network to a main location. A wireless sensor, also known as a mote (reMOTE), smart dust, smart sensor or sensor node within the network performs the function of sensing, data processing and wireless data transmission. It is powered by an individual power source which often consists of a battery with a limited energy budget.

2.1. Use of MEMS technology

Use of Micro-Electro-Mechanical Systems (MEMS) technology enables the production of low-cost, low-power multifunctional sensors which have very small size and light weight. MEMS technology whereby microsensors, microactuators, microelectronics and other technologies can be integrated onto a single microchip is expected to be one of the most important technological breakthroughs of the future. MEMS is a technology that in its most general form can be defined as miniaturized mechanical and electro-mechanical elements (i.e., devices and structures) that are made using the techniques of micro fabrication [9]. The critical physical dimensions of MEMS devices can vary from well below one micron on the lower end of the dimensional spectrum, to several millimeters. The term used to define MEMS varies in different parts of the world. In the United States they are predominantly called MEMS, while in some other parts of the world they are called „Microsystems Technology” or „Micromachined devices”.

2.2. Sensor node architecture

A sensor node typically consists of five main components (Fig.1): one or more sensors gather data from the environment and report the data to the microprocessor. A microprocessor is a central part of a wireless sensor node. It processes all the data received from memory, sensor, or transceiver. A transceiver communicates with the environment. It is used radio frequency (RF) as a transmission medium to send data wirelessly. The transceiver can take data from a microprocessor to send it over the air and vice versa. A memory is the main resource for storing programmes and intermediate data coming from the sensors or the transceiver. The size of the memory depends on the application of the sensor. The battery supplies all the parts with energy. To assure a sufficiently long network lifetime, energy efficiency is crucial in all the parts of the network. Although most sensors have a traditional battery, there is an early stage research regarding production of sensors without batteries, using similar technologies applied to passive radio frequency identification (RFID) chips without batteries. The sensor nodes are usually scattered in a sensor field. Each of them has the capabilities to collect data and route data back to the base station. The base station may communicate with the task manager node via Internet or Satellite. In [7] the node deployment models in WSNs have been explored. Various architectures and node deployment strategies have been developed for wireless sensor network, depending upon the requirements of application. The authors focused on five deployment schemes for sensor networks environments, random deployment, grid deployment, group-based deployment, and grid-group deployment.

2.3. Energy efficiency in routing

A number of research works have already been accomplished in routing in WSN, since energy efficiency is more important for wireless sensor networks than any other networks. In wireless communication, data transmission consumes more power than data processing. The battery power of the node will be reduced whenever they transmit a great number of data proportionately. In order to reduce the data size we can prefer techniques like
data fusion or aggregation. Data fusion is that in which the sensed data are fused at a certain point for transmitting them at a reduced size. However, there is a problem showing lack in precision and accuracy of data from various sensor nodes [8]. In order to prolong the lifetime of the WSN, designing efficient routing protocols appear to be critical. It has been established that most of the energy consumption in a WSN comes from data reception and transmission. Therefore, a good routing protocol can reduce the number, as well as the size of the unnecessary transmissions which take place. Thus, the routing protocol helps alleviating the energy crisis in WSNs. Hierarchical routing algorithms are techniques with special advantages related to scalability and efficient communication. The main aim of hierarchical routing is to optimize energy consumption of sensor nodes by arranging the nodes into clusters [8]. Data aggregation and fusion is performed within the cluster in order to decrease the number of transmitted messages.

3. WIRELESS NETWORKS APPLICATIONS

In the recent years, WSNs have been applied in many engineering fields, ranging from national defence and military affairs, structural health monitoring, industrial applications, environmental monitoring, traffic controls, health applications, animals monitoring, etc [12]. Here, we are going to present some of WSNs applications in aircraft.

3.1. WSN for aircraft structural health monitoring

Because of the increasing use of composite materials for aircraft structures, it is necessary to develop new methods for aircraft structural health monitoring. Most of the failures of the laminated composite structures originate from delamination of layers. Regarding metal aircraft structures, cracks develop and eventually lead to failures. In both of these cases, visual inspection is not a reliable method for failure detection. This calls for a vibration analysis-based on failure detection method. Currently scheduled aircraft structure maintenance methods have a high maintenance cost. Several studies have been conducted to develop health monitoring algorithms which use the data from strain sensors embedded into the composite structure. WSN can be embedded into the composite structure which will harvest the vibration energy and will transmit the real-time data to the central health monitoring unit. These sensors will be used to monitor the internal parameters like cracks, strain, as well as external parameters such as temperature, load, etc. Because of this, the use of WSN, powered by energy harvesting techniques will increase the number of sensors and their lives. Hence, the real-time data will enable the use of condition-based maintenance, thereby preventing catastrophic failure of aircraft structures. Although the use of MEMS is one of the promising technologies for implementation of WSN-based aircraft structural monitoring, optimum energy harvesting and power management methods for MEMS sensors have to be further improved. The integration of sensors and airframe has to be studied as well as the effect on the structural strength of composite materials due to embedded sensors.

3.2. WSN for static testing of a real aircraft undercarriage

Researchers from the research institute of China have applied a wireless sensor network for static testing of a real aircraft undercarriage [10]. The developed wireless sensor network system consisted of 14 sensor nodes and 4 cluster heads. The authors concluded that the system design may be much more complicated when the number of testing points which have to be measured will greatly increase. Furthermore, fatigue testing for full-scale structure requires higher data transmission rates, data synchronization and data buffer processing capacity. Therefore, hardware capabilities for the WSN based aircraft strength testing systems should be improved in further research. Networking and routing protocols should be seriously studied in order to solve these problems.

3.3. Wireless systems for tracking the load history of helicopter

Wireless sensor modules were integrated into the pitch link of a Bell M412 helicopter. These modules have passed MIL-STD-810F tests for vibration, shock, humidity, and temperature extremes. Pitch link loads were recorded and periodically transmitted into the cabin during flight [11]. Wireless sensors included strain gauges, accelerometers and thermocouples. Hard-wired sensors included gyroscopes, accelerometers and magnetometers. Data from an embedded Global Positioning System (GPS) provided position, velocity, and precise timing information. The inertial sensing suite provided vehicle orientation (pitch, roll, and yaw) data. These data were collected at multiple sampling rates and time stamped and aggregated within a single scalable database on a base station, termed the wireless sensor data aggregator (WSDA). Wireless technologies for tracking the load history of helicopter rotating components, combined with inertial and global positioning system (GPS) information, can be used to compute structural loads with improved accuracy. The integration of these sensor systems will lead to reduced cost flight testing, improved safety, and enhanced condition based maintenance (Fig.2). Ideally, the integrated structural health monitoring system would report aircraft load history data without human intervention. Data collected during the flight would be automatically recorded on board, without wireless communications, since each wireless load tracking node would be capable of recording data within its local non-volatile memory. Having landed, the on-aircraft base station would query the network of wireless load tracking nodes, and prepare the data files for remote transmission over the cellular or satellite connection. Then, the data would be analyzed and maintenance instructions sent back to aircraft technicians.
3.4, The MicroStrain’s components for aircraft structural health monitoring

A well known USA company MicroStrain produces smart, embedded micro-displacement transducers, inertial sensors, and energy harvesting wireless sensor networks. The SG-Link® -mXRS Wireless Strain Node presented in Fig.3 features complete strain gauge signal conditioning, embedded processing, wireless communications, and precision timekeeping. SG-Link®-mXRS wireless nodes operate within a fast, synchronized, scalable network of wireless sensor nodes located up to 1 km from MicroStrain WSDA®-Base. SG-Link®-mXRS nodes include an internal rechargeable Li-Ion battery and measure strain, torque, load, pressure and magnetic fields through a connector to user-supplied bridge sensors.
The most important features and benefits of the presented wireless sensor node are given in the Table 1.

Table 1. Features of the SG-Link – mXRS Wireless Strain Node

<table>
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<tr>
<th>Feature</th>
<th>Description</th>
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<tr>
<td>Data storage capacity</td>
<td>2 megabytes (approximately 1.000.000 data points)</td>
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<tr>
<td>RF data downloading</td>
<td>8 minutes to download full memory</td>
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<tr>
<td>Range for bi-directional RF link</td>
<td>programmable communication range from 70m to 2.000m</td>
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<tr>
<td>Internal Li-Ion battery</td>
<td>3.7 volt 250 mAh lithium ion rechargeable battery or external power 3.2 to 9 volts</td>
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<tr>
<td>Maximum acceleration limit</td>
<td>500 g standard (high g option available)</td>
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<tr>
<td>Weight</td>
<td>50 g (with enclosure); 17 g (circuit board assembly only)</td>
</tr>
<tr>
<td>Dimensions</td>
<td>58 mm x 50 mm x 26 mm (enclosure without antenna) 46 mm x 36 mm x 16 mm (circuit board assembly only)</td>
</tr>
<tr>
<td>Software</td>
<td>Node Commander® Windows XP/Vista/7 compatible</td>
</tr>
<tr>
<td>Compatible base stations</td>
<td>WSDA®, WSDA® -Base</td>
</tr>
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The MicroStrain’s scaleable wireless networks are presented in Fig.4. CSMA denotes Carrier Sense Multiple Access (Fig.4a). Carrier Sense Multiple Access is the protocol for carrier transmission access in Ethernet networks. On Ethernet, any device can try to send a frame at any time. Each device senses whether the line is idle and therefore available to be used. If it is, the device begins to transmit its first frame. If another device has tried to send a frame at the same time, a collision is said to occur and the frames are discarded. Then, each device has to wait for a random spell of time and to try again until it becomes successful in getting its transmission sent. FDMA denotes Frequency Division Multiple Access (Fig.4b). The Frequency Division Multiple Access is an access technology which is used by radio systems to share the radio spectrum. The terminology “multiple access” implies the sharing of the resource among users, and the “frequency division” describes how the sharing is done: by allocating users with different carrier frequencies of the radio spectrum. This technique relies upon sharing of the available radio spectrum by the communications signal which must pass through that spectrum.

The MicroStrain USB (Universal Serial Bus) base station is a transceiver which provides a communication link between a host computer and the Agile-Link™ family of wireless nodes including V-Link® (Wireless Voltage Node), SG-Link® (Wireless Strain Node), G-Link® (Wireless Acceleration Node) and TC-Link® (Wireless Thermocouple Node). The USB base station employs a 2.4 GHz radio with 16 selectable channels to communicate with the remote nodes. The USB base station is connected to a host computer via a USB connection and is operated with MicroStrain’s Agile-Link™ software.

4. TECHNICAL CHALLENGES

Some of the technological challenges for implementing safety-critical control systems based on WSN are as follows:

Medium access control (MAC) protocols for wireless control systems

Each sensor node within the WSN has limited energy and computational resources. In order to make optimal use of these finite resources, a number of protocols based on MAC have been developed. These protocols put stress on...
energy efficiency by reducing the energy loss due to wireless medium. Since MAC protocols focus on energy efficiency and not on reduction in communication delay, the performance of control systems based on these protocols is limited. Research should be conducted to design MAC protocols which are not only energy efficient, but also offer high quality of service in terms of time delay, as well as, bandwidth utilization and data loss due to packet collisions. Thus, only a few studies have focused on this approach.

**Optimum power source**

Powering all the sensors using the conventional batteries will not only increase the size and weight of the system but will limit their service life and will require expensive maintenance. A widely investigated alternative is to use energy harvesting techniques to generate electrical power for operating these sensors. WSN can operate almost maintenance free by using both energy harvesting methods and implementing strict power management. Vibration-based harvesting technique is seen as one of the promising techniques for aerospace applications. Current vibration energy harvesters are constructed as mechanical resonators with a transducer element that converts motion into electricity. They are further divided into three groups of generators based on their physical transduction principle: piezoelectric, electrostatic, and electromagnetic.

**Certification of aircraft wireless systems**

Use of wireless communication networks for safety critical functions of an aircraft requires a very high degree of safety insurance and certification. The Federal Aviation Administration (FAA) has certified a number of aircraft wireless radio frequency (RF) systems which include wireless smoke and fire detection systems and cabin emergency lighting systems with wireless controls. However, all these systems are non-safety critical systems and typically operate in an unlicensed spectrum. Specific regulations for aircraft wireless systems do not exist and there is a need to develop specific regulations for such new applications of WSNs. Such regulations are necessary to ensure that there is no interference between portable electronic devices carried by passengers, existing airplane radio transmitters and transmitters within the proposed WSN. There is no worldwide spectrum allocated specifically for flying by wireless systems. The new certification rules must ensure that the WSNs are protected against unauthorized introduction and modification of data, denial or loss of service, gradual degradation of service and introduction of misleading or false data. The current FAA regulations expect physical isolation between safety critical and other communications networks like passenger entertainment networks. The new regulations must also take into consideration security threats including safety threats, business threats, channel jamming attacks, etc.

5. CONCLUSION

The aircraft industry will greatly benefit from the use of WSNs. These benefits through weight savings, reduction in subsystems design complexity and improved condition based maintenance will directly benefit the airlines in terms of additional revenues, as well as lower operational and maintenance costs.

There are a few significant technical challenges for the successful implementation of wireless sensor networks. Future research and development should consider technical challenges as follows:

- Research needs to be conducted in the area of information fusion of wireless sensor networks for aircraft systems.
- Routing protocols should be developed to make efficient use of the limited power supply, limited communication bandwidth and limited computing power.
- Energy harvesting methods need further improvement in the terms of efficiency and reliability.
- New wireless aircraft certification regulations have to be introduced regarding the various security and safety threats.
- A dedicated global spectrum for WSN for aircraft applications has to be accomplished.

References


