Wireless sensor and actuator networks: enabling the nervous system of the active aircraft

Bür, Kaan; Omiyi, Peter; Yang, Yang

Published in:
IEEE Communications Magazine

DOI:
10.1109/MCOM.2010.5496888

2010

Document Version:
Peer reviewed version (aka post-print)

Link to publication

Citation for published version (APA):
Bür, K., Omiyi, P., & Yang, Y. (2010). Wireless sensor and actuator networks: enabling the nervous system of the active aircraft. *IEEE Communications Magazine*, *48*(7), 118-125. https://doi.org/10.1109/MCOM.2010.5496888

Total number of authors:
3

Wireless Sensor and Actuator Networks: Enabling the Nervous System of the Active Aircraft

Kaan Bür, Peter Omiyi, Yang Yang[1]

Communications and Information Systems Research Group
Department of Electronic and Electrical Engineering
University College London
{k.bur, p.omiyi, y.yang}@ee.ucl.ac.uk

Abstract

The ever-increasing volume of air transport necessitates new technologies to be adopted by the flight industry to fulfil the requirements of safety, security, affordability and environment friendliness while still meeting the growing demand. What we need to achieve this goal is a new type of aircraft cruise control, interconnecting all the onboard active control systems and making more accurate control decisions than is currently possible, thus improving the overall flight efficiency. “Active Aircraft” envisions such a nervous system of distributed wireless sensor and actuator network (WSAN) components, enabling the early detection of potential problems, and quick, accurate reactions to these. As part of this vision, WSAN deployed on aircraft wings help the reduction of aerodynamic drag and significantly reduce fuel consumption.

In this article, we first describe this conceptual change in aircraft control technology. We then introduce a WSAN application to reduce skin friction drag, and a network topology to enable it. In our application, WSAN form virtual flap arrays on the wings to measure the skin friction in real time, and to react using synthetic jet actuators, which suck and expel air on the wing to reduce the friction. The Active Aircraft vision imposes stringent performance requirements on the underlying WSAN communication algorithms. The medium access control and routing protocols, in particular, must meet the quality of service criteria set by active control applications. Thus, we also present the application characteristics of Active Aircraft and raise the issue of design considerations with regard to the communication protocols.

Keywords: active aircraft, airflow control, convergecast routing, skin friction drag, wireless sensor networks.

---

1. Introduction

THE demand on air transport is predicted to double in the next 10-15 years and triple in the next 20 [1]. Although a commercial opportunity, this drastic increase presents significant challenges in terms of flight capacity, safety, security and affordability, as well as time efficiency and environmental effects. The current European air transport system, for instance, consists of about 5 000 aircraft carrying 1 billion passengers every year. Thus, it is easy to see the need for new technologies in order to meet the demand predicted for the near future. First of all, the environmental impact of the ever increasing number of flights needs to be reduced. Alternative fuel sources, engine technologies and structures, aircraft configuration, aerodynamics, and air traffic management are some of the research fields related to this issue. Secondly, flight safety and security must not be compromised at all costs. Hostile action detection, cabin and cockpit monitoring, aircraft operation and landing control are possible research issues under this category. Finally, time and cost efficiency need to be addressed. Punctuality can be achieved through the integration of the airspace and ground components as well as through increased aircraft autonomy, whereas costs can be reduced through the “zero maintenance” aircraft concept as well as through a lower fuel emission level.

A much higher level of flight efficiency can be achieved if all these issues are addressed within the framework of a single, holistic system, taking into account their interdependencies, thus optimising the overall flight conditions. We need an on-board "nervous system" to interconnect all the active control systems used on the aircraft, such as airflow and load control, as well as engine, structure and system health monitoring. By exploiting advanced wireless sensor and actuator network (WSAN) technologies, such a system undertakes two essential tasks with a novel approach: (i) the collection of real-time status and environment information from different parts of the aircraft, thus enabling the early identification of potential problems and the detection of failures via a comprehensive data analysis at a central controller; and (ii) the distribution of control messages to different parts of the aircraft, thus enabling early and accurate reactions to the status and environment changes by using, for instance, actuators. Due to its ability to give quick and accurate responses to events, the on-board nervous system can significantly improve the overall flight efficiency in commercial aircraft.

Manuscript submitted May 19, 2009, to the ongoing series on ad hoc and sensor networks of IEEE Communications Magazine. Revised version submitted September 30, 2009.

This work was supported jointly by Airbus and EPSRC, the Engineering and Physical Sciences Research Council of the United Kingdom, under the “Active Aircraft” programme, with the grant number EP/F004532/1.

[1] Corresponding author. *Tel:* +44-20-7679 3973. *Fax:* +44-20-7388 9325.

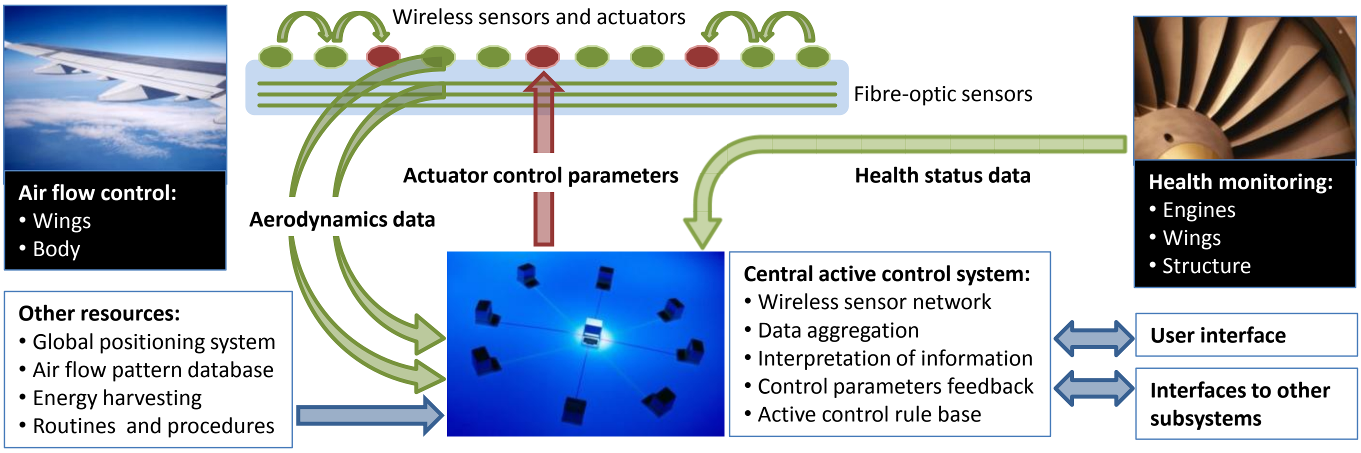


Figure 1. Active Aircraft – An integrated aircraft nervous system for active airflow control and health monitoring.

As mentioned above, WSAN are an essential part of the aircraft nervous system, presenting an efficient means of data gathering, processing and decision making under extreme physical conditions. Figure 1 shows the functions of and the interactions between the various components of the envisioned system, which we call “Active Aircraft”. These are:

- Application-specific wireless and fibre-optic sensors to collect the measured aerodynamics and health status data from the wings, airfoil and engines;
- A central active control system to interpret the information aggregated through the WSAN and feed back the updated actuator control parameters;
- Wireless actuators to realise the active airflow control.

The reduction of fuel consumption is important for both the environmental effects as well as the cost efficiency of air transport [1]. One of the most significant factors increasing the aircraft fuel consumption is the aerodynamic drag. At commercial flight conditions, approximately 25% of the total aircraft drag comes from the skin friction drag [2], which arises from the friction of air against the skin of the aircraft moving through it. The primary source of skin friction drag during the flight is boundary layer separation. The boundary layer is the layer of air moving smoothly in the immediate vicinity of the wing. The smooth flow is disturbed by the boundary layer separating from the surface, as shown in Figure 2, creating a low pressure region and, ultimately, increasing the skin friction drag. Previous related research [3], [4] uses synthetic jet actuators (SJA) running at key positions on the wing continuously to energise the boundary layer and, thus, delay its separation. These approaches do not use sensors to detect and trace the separation, and are therefore static and proactive in nature. They potentially compromise the efficiency of active flow control and waste energy resources when there is no boundary layer separation or when it lies outside the actuators’ optimal control field.

The use of WSAN technologies on the wings of the aircraft helps us to reduce the skin friction drag more efficiently, thus improving the overall fuel economy of a flight. Our contribution to the Active Aircraft proposes to use arrays of wireless sensors and SJA to minimise the skin friction drag and enhance lift, thus addressing the problem of active flow control over the wing. The proposed WSAN enabled approach is, in contrast to the previous research, dynamic and reactive. It can dynamically and effectively trace and delay boundary layer separation. WSAN is thus a key technology for this application; and its functionality under airborne operating conditions is a research challenge.

In this article, we first introduce our virtual flap array application to reduce the skin friction drag as part of the Active Aircraft vision. We then present a network topology we designed for our application. We identify the application requirements and further design considerations. We also classify the existing communication protocols in light of these considerations, and review some of the related research using wireless sensor networks (WSN) in aircraft.

2. Virtual Flap Arrays for the Active Aircraft

Skin friction occurs on the body, particularly on the wings, of an aircraft because of boundary layer separation due to high angles of attack between the airflow and the surface during take-off, landing, sudden pilot manoeuvres, or from turbulence and wind gusts. It also results from the formation of normal shock waves on the wing at transonic speeds. Various methods for controlling the boundary layer separation have been explored in the literature [2]. Suction from the surface of the wing is used to remove the low energy air directly from the boundary layer. Along with this method, additional momentum is introduced to the boundary layer by blowing high pressure air taken from an engine compressor to energise the low energy region. The plumbing systems required for suction or blowing, however, introduce complexity, additional vulnerability to failures, increased weight, and higher costs of deployment and maintenance to the aircraft.

Recently, the addition of momentum in an oscillatory manner using SJA has been studied [3], [4]. SJA have the

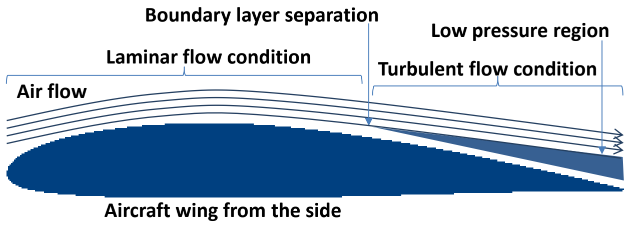


Figure 2. Boundary layer separation on an aircraft wing.

advantage of being small, light, and energy efficient, do not require plumbing and fluid storage tanks, and are independent of propulsion systems. They synthesise a time averaged flow field similar to a continuous jet of air by producing a succession of vortex rings that propagate away from an opening on the actuator. Although a significant improvement, SJA still present a major drawback as a static and proactive approach: Being deployed in fixed locations irrespective of the actual location of the boundary layer separation, they operate continuously, regardless of whether or not there is a separation. For instance, it is possible that the separation or shock wave is located outside the control region of SJA, or that there is no separation. In this case, no reduction in drag is achieved but rather an increase in drag is possible when turbulent flow is generated by the vortices of SJA in the area of attached flow. Furthermore, the point of separation or shockwave, if any, may move with changes in wind speed and turbulence at cruise and especially in the event of sudden pilot manoeuvres and landing or take-off.

This important problem and other limitations of the existing static and proactive solutions motivate us to investigate and develop a dynamic and reactive approach to separation control using an array of virtual flaps deployed on the wings. In this approach, only SJA in the vicinity of a separation are activated, minimising power consumption and induced drag. Furthermore, the area of operation never lies outside of the control area of the virtual flap array. WSAN are introduced as the enabling technology for SJA to avoid the complex plumbing required for a high density deployment of traditional airfoil pressure sensors. Thus, SJA have communication and processing capability, enabling the distributed control of the boundary layer.

Figure 3 shows the virtual flap array approach to using SJA. A matrix of virtual flaps deployed on the wings, each of which consists of a system of pressure sensors and SJA, are used to keep the boundary layer attached. Based on the measurements from its pressure sensors, a virtual flap detects the presence of boundary layer separation or a normal shock wave in its vicinity and activates its SJA to reenergise the air flow in that region. This effectively reattaches the boundary layer, which reduces drag and avoids stall. The 'virtual' flap is called as such because it emulates traditional 'hinged' flaps in terms of altering the airflow around the wings. The virtual flap, however, has a number of potential advantages over hinged flaps in terms of weight and maintenance cost, due to the absence of moving parts and induced drag. In addition, the ability to deploy several small SJA in various configurations over the surface of the wing results in improved flexibility in flow control, which is not feasible with hinged flaps due to size and weight constraints as well as high maintenance costs.

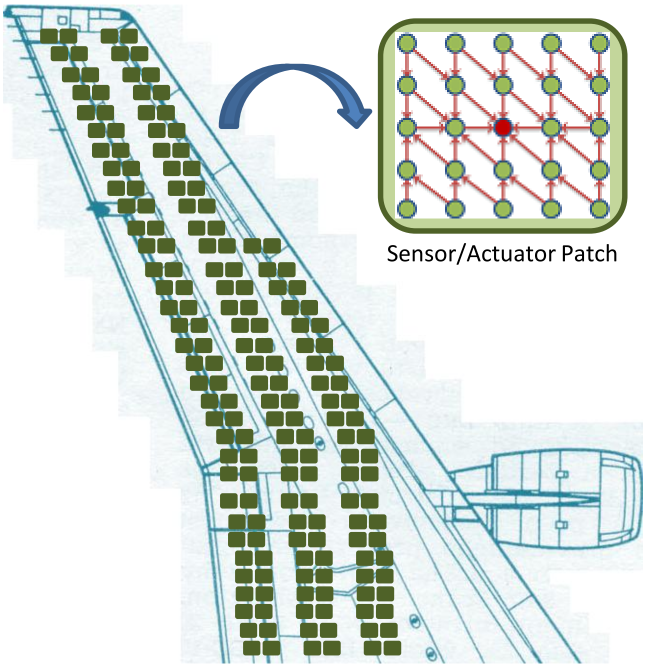
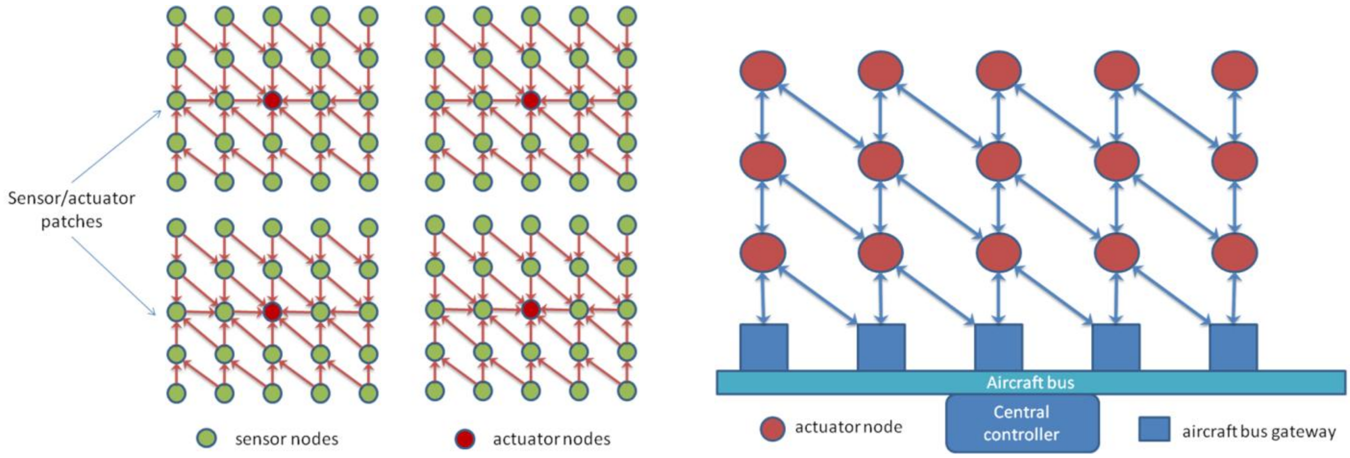


Figure 3. Virtual Flap Array – The dynamic organisation of wireless sensors and synthetic jet actuators to control the boundary layer separation on the wing.

In our design, we envisage the actuators to be placed 50 mm apart from each other, across the wing. Thus, given a patch size of 5x5 as shown in Figure 3, the distance between the sensors is 10 mm. The actuators operate with an SJA forcing frequency between 1 and 5 kHz. The sensors' measurement frequency is of the order of 10 Hz to monitor the separation during normal flight, whereas, depending on the available bandwidth, it should become practically continuous during operation in landing configuration.

2.1. Network Topology

The WSAN for active aircraft flow control is expected to comprise of a high density of sensors and a lower density of actuators, both uniformly distributed over the relevant surfaces of the aircraft. Thus, a grid or mesh like wireless network topology is anticipated. To enable fast, distributed active control, the network is organised into local 'patches' comprising of a central actuator surrounded by several sensors responsible for providing the relevant measurement data necessary for the real-time control decisions, which is illustrated in Figure 4(a). The local patch communication in this topology presents a convergecast pattern, as many sensors send their data to one local actuator. Furthermore, sensor measurements in a patch are highly correlated and, thus, the data generated by the sensors in a patch display a high level of redundancy. The actuator can combine these measurements into a single, more accurate measurement,



(a) (b)

Figure 4. (a) Convergecast topology with sensor/actuator patches for distributed active airflow control; and (b) Convergecast/unicast topology with actuators acting as cluster heads for centralised active airflow control.

which gives a single control decision metric. Thus, local patch data redundancy is exploited using the convergecast communication pattern to filter out erroneous readings and to improve the overall accuracy of the measurements.

The actuators process the data received from the sensors, take the appropriate action, and send the control output to a central aircraft control system, which adapts the actuator parameters for the next control loop. Unlike the communication between the sensors and the actuators in a patch, which takes place locally in the vicinity of the surface being monitored, the communication between the actuators and the central controller is not local. Thus, all aircraft control systems reach the central controller via the central 'nervous system', and wireless gateways are strategically located to provide connectivity between WSAN and the aircraft nervous system, as illustrated in Figure 4(b).

The characteristics of WSAN to be deployed as the virtual flap array are quite challenging when compared to those of traditional WSN with grid structure, which makes further research necessary. First, the virtual flap array consists of a number of patches, with an actuator (i.e., sink) at the centre of each patch, whereas a traditional WSN usually has a single sink located in its centre. This difference yields dissimilar convergecast traffic patterns, demanding further attention in terms of MAC and routing design. Second, a WSAN can interact with and have an impact on the physical world, raising real-time performance issues, which is mostly not the case for traditional WSN. Finally, the environmental conditions surrounding the virtual flap arrays are harsher than their WSN counterparts, considering particularly radio propagation. WSAN nodes need to be embedded to the surface of the aircraft wing, implying propagation within the skin in an environment where reflection of the radio signals is very poor.

Given the high density of sensors and actuators to be deployed for active airflow control, the aggregate power consumption requirements could also be quite high. This is expected to significantly impact fuel economy in case some or all of this power is supplied by the aircraft. At one extreme, if only battery powered nodes are used, which maximises the fuel economy, the energy resource becomes limited, and conserving energy is even more crucial. Even if ambient energy harvesting is employed to recharge the batteries, the instant power consumption is still limited by the rate at which energy reserves are replenished. However, some nodes like actuators, which have higher power requirements for actuation, processing and communication, will possibly operate on the aircraft power supply. Some sensors may also be powered by the aircraft to provide added design redundancy and enhance the overall network reliability. In any case, maximising the energy efficiency of WSAN is an important design goal regardless of how the network is powered. We discuss energy efficiency and other design objectives in the next section.

3. Design Considerations

Active Aircraft applications require distributed local as well as centralised global control. Distributed control algorithms require the sensors to process the measured data locally, make quick control decisions, and then directly communicate with their neighbouring actuators for them to take control actions. Both active control approaches impose stringent performance requirements on communication algorithms, medium access control (MAC) and routing in particular, especially in terms of delay, loss and throughput. The ultimate goal is to disseminate data from sensors to the actuator in an energy efficient and quality of service (QoS) aware manner, so that the WSAN lifetime is maximised.

At this point, the main application characteristics of Active Aircraft need to be summarised in terms of network topology, information flow, the amount of data, and the energy profile of the nodes.

Network Dynamics

The sensors and actuators of Active Aircraft are stationary. As shown in Figure 4, they have a grid-like topology along the surface of the wings and body of the aircraft. This makes it relatively easy to define routing paths and, if necessary, map geographical regions relative to the aircraft to network addresses in a deterministic way.

Node Deployment

Manual node placement is possible. Nevertheless, the sensors are still wireless. Since many sensors are likely to experience temporary or permanent communication problems due to the extreme environmental conditions, self-organisation and redundancy are needed in the network.

Data Delivery Model

The measurements on temperature, air pressure and other environmental conditions aim at observing the status of the aircraft continuously and adapting its behaviour accordingly. Thus, most of the information flow is periodic. To a relatively small extent, however, event-driven information gathering can be required to enable the central control system to react to unexpected and rare events.

Node Capabilities

It is possible to install a relatively small number of actuators with unlimited energy and high computational power to the WSAN. Being considerably more powerful, the actuators can be configured as gateways to the wired or wireless infrastructure backbone network. They can take over heavy duties such as collecting, processing and interpreting data. However, energy considerations will be in charge for the rest of the WSAN.

Routing and MAC protocols designed for WSN have been extensively studied in the literature [5], [6], [7]. These studies, however, examine the protocols from a general perspective, i.e. without considering the application specific requirements. An evaluation of five WSN MAC protocols [5] shows, for instance, a message delivery ratio of less than 0.5 and a latency ranging from 2 s to 11 s under a network load of 1 message per node per second. These results suggest that further research is necessary to develop the protocols meeting the performance requirements of Active Aircraft. Our aim in the rest of this section is, thus, to classify the existing routing and MAC protocols based on the design considerations of Active Aircraft. A detailed numerical performance evaluation, although an important future research item, is beyond the scope of this article.

3.1. Medium Access Control

This section lists the application requirements for MAC protocols to enable both distributed and centralised active flow control schemes. These requirements fall loosely into three groups: system constraints imposed by data patterns and network topology, performance requirements, and essential design features.

Scheduling

The regular sensor measurements generating a periodic data flow from the sensors to the actuator implies a schedule based MAC approach in order to effectively exploit this pattern. In each patch, some spatial correlation is expected between the sensor measurement data. The MAC protocol must have the ability to manage the local data communication in a manner that allows this data redundancy to be exploited.

High Area Spectral Efficiency

The periodically generated sensor data requires real-time processing and delivery to the actuator to implement real-time, distributed airflow control. Maximising the area spectral efficiency, i.e. the throughput per unit bandwidth per unit area, in the multi-hop sensor network is essential to minimising latency and maximising energy efficiency. A MAC protocol with high area spectral efficiency is required to minimise the data forwarding delay within a patch and to maximise the number of patches communicating simultaneously.

Receiver Channel Sensing

Interference between the patches can be managed by centralised scheduling coordinated by the central controller. However, without receiver channel sensing, this results in either over-provisioning at one extreme or poor interference management at the other, both resulting in low area spectral efficiency. Receiver channel sensing requires a scheduled transmitter to listen for feedback signals from receivers in other patches in its vicinity to determine whether it can transmit without causing them unacceptable interference. This information is used by the central controller to optimise the schedule to maximise area spectral efficiency.

Minimum Handshaking, Idle Listening and Overhearing

Sender-receiver handshaking via request-to-send (RTS) and clear-to-send (CTS) messaging prior to data transfer (DATA) is unnecessary for deterministic periodic data, and yields potentially significant overhead given that sensor data typically comprise of short bursts. On the other hand, receiver acknowledgements (ACK) provide a powerful means of enabling interference awareness. Therefore, MAC with DATA/ACK are preferable to MAC with RTS/CTS/DATA. Furthermore, idle-listening to channel activity and overhearing data of other links must be minimised to enhance energy efficiency since, while enhancing the interference management capabilities, they consume a lot of energy.

An evaluation of the state-of-the-art [6] highlights the advantages and disadvantages of some existing MAC protocols designed for WSN. It should be noted, however, that none of these protocols were designed for airborne operation. Thus, from a systems design perspective, they shouldn’t be expected to satisfy all the requirements of Active Aircraft. Table 1 summarises our comparison of protocol characteristics, from which we can see that many of the features desired by Active Aircraft are not contained in the existing MAC protocols. Thus, the design, or redesign, of a MAC protocol suitable for the Active Aircraft scenario is an important item for further research.

3.2. Routing

Many algorithms have been proposed for routing data in

Table 1. Evaluation of some WSN MAC protocol characteristics with respect to Active Aircraft application requirements.

Protocol	S-MAC	T-MAC	DMAC	LPL	SCP-MAC	LMAC	Crankshaft
Low latency multihop	No	No	Yes	No	No	No	No
Bidirectional	Yes	Yes	No	Yes	Yes	Yes	Yes
Periodic data	No	No	No	No	No	Yes	Yes
Spatially correlated data	No	No	Yes	No	No	Yes	Yes
Area spectral efficiency	Low	Low	Low	Low	Low	Low	Low
Receiver channel sensing	Yes[1]	Yes[1]	No	No[3]	No[3]	No[3]	No[3]
Handshaking overhead	High[1]	High[1]	Low[2]	High	Low	High	Low
Idle listening & overhearing	Low	Low	None	Low	Low	None	None
Scalable & traffic adaptable	No	No	Yes	No	Yes	No	No

[[1]with RTS/CTS] [[2]with ACK] [[3]hidden terminal problem]

WSN, attempting to consider one or more of their characteristic differences which make the adaptation of other existing routing schemes infeasible. Most of these routing protocols can be broadly classified as follows [7]:

- *Data-centric protocols*, which are query-based and depend on the type of the data.
- *Hierarchical protocols*, which aim at clustering the nodes and aggregating the data to save energy.
- *Location-based protocols*, which utilise the position information to direct the data to a desired region.
- *QoS-aware protocols*, which try to meet some QoS requirements such as delay, loss and throughput.

Our goal in this section is to evaluate these four classes of WSN routing protocols according to the application characteristics of Active Aircraft listed in Section 3, and the key design considerations explained below.

Energy Efficiency

Considering the Active Aircraft applications, the main aim of routing is to set up and maintain energy-efficient paths to deliver the sensor data to the actuators (and, eventually, to a central controller) reliably while keeping the network up and running for as long as possible. In this regard, energy efficiency can be considered as the primary design objective of all WSAN routing approaches, which relates to both the selection of the routes as well as the overhead of routing.

Route Stability

Secondary aspects in WSAN routing, such as stability and dependability of the routes, are also important and need to be considered as such in accordance with the application requirements and, of course, without jeopardising the primary objective of energy efficiency. Multi-path routing for load and energy balancing can also improve the resilience of the WSAN. Secondary (or stand-by) paths can help the network to find better trade off opportunities between robustness and energy efficiency. However, routing table sizes should be kept small since WSAN nodes have limited memory.

Data Aggregation

Due to the nature of its measurements and the placement of its sensors, Active Aircraft is an application very likely to produce high volumes of redundant data. This phenomenon not only causes a significant increase in used bandwidth and consumed energy; it also requires more processing power and increases delay. Data aggregation is a desired feature for Active Aircraft to address these issues.

Service Classes

Active Aircraft can be distinguished into long-term and short-term control applications. The former is based on observing the long-term status and is therefore tolerant to delay and loss. The latter, however, requires short-term and accurate information to take the most appropriate action and is therefore sensitive to delay and loss. Thus, at least two service classes need to be defined to represent best-effort and real-time data traffic within the context of Active Aircraft, and to support the QoS requirements of both types of applications. The control application is then assigned the higher priority service class than the monitoring application and has precedence over it in terms of resource allocation.

Table 2 summarises our evaluation, presenting our comments on the feasibility of each class of routing protocol. In light of our evaluation at the application level, we believe that the state-of-the-art WSN routing protocols do not provide a complete set of features desired by Active Aircraft, which is not surprising since none of them was designed for airborne applications. Further research is necessary concerning the design of a routing protocol that suits the application requirements of Active Aircraft.

4. Related Research

Current applications of WSN technologies in aircraft are primarily focused on structural and engine health

Table 2. Evaluation of routing protocol characteristics with respect to Active Aircraft application requirements.

Protocol Characteristics	Required?	Reasoning for Active Aircraft
Data-centric	✖	In Active Aircraft, most of the information gathering will be periodic. A data-centric approach would cause too much message overhead to query the data that can be easily sent automatically with a predefined frequency.
Hierarchical	✓	The amount of the data to be gathered by Active Aircraft will be high. Data aggregation will be needed to save bandwidth and energy. Multi-hop, multi-tier communication will be encouraged to limit the transmission power of the sensors.
Location-based	✖	The sensor nodes of Active Aircraft will be fixed on the surface of the wings in advance. A grid-like network topology will enable the routing protocol to distinguish the sensor regions without the assistance of geographical positioning.
QoS-aware	✓	Distributed local control requires data accuracy. Centralised global control necessitates low latency. Thus, reliability, delay and loss are important QoS factors for the control commands in Active Aircraft.

monitoring for maintenance. For one of these systems, Harman [8] identifies two sensing topologies, namely 'wired sensors / wireless node' and 'all-wireless sensing network'. The author summarises applicable wireless technologies and describes one possible technique for radio propagation measurements. It is further suggested that, by including all the data necessary to make direct maintenance decisions within the sensor node rather than processing it centrally through other systems, wireless sensors can operate independently and reduce costs compared to time-based maintenance systems significantly.

Bai et al. [9] describe the architecture of a WSN for aircraft engine health monitoring, which comprises of a number of sensors and a central engine control unit. Its communication protocol stack includes a power-aware routing module, a node positioning module, a network membership module and a low-power media access module. The authors also present a single-chip solution for the communication controller and the transceiver.

Sampigethaya et al. [10] address the security vulnerabilities related to the collection and distribution of commercial airplane health data. They identify the threats, the system requirements to mitigate them and present challenges and open issues in enabling the secure use of WSN for health monitoring in commercial aircraft.

Finally, Shang et al. [11] classify structural health monitoring systems into two groups, namely 'operational load monitoring' and 'damage monitoring' and introduces some of the new sensor technologies such as optical fibre, piezoelectricity, micro-electro-mechanical sensors and wireless sensing systems.

There are also a few proposals to support a distributed sensing and basic flight control system of small-scale unmanned air vehicles (UAV). For instance, Coelho et al. [12] present a short-range wireless network platform to support a distributed sensing and actuation control system of a model-sized aircraft. The implementation is based on Bluetooth and a two-level hierarchical state machine adapting a round-robin scheduling algorithm to send and receive messages. The wireless network comprises of one master and up to seven slave stations, which is the limit for Bluetooth piconet structure.

As these examples show so far, WSN have not been implemented in aircraft in complex applications like real-time active control. Spacecraft WSN applications, on the other hand, are currently more advanced, with operational WSN in the International Space Station and NASA's Space Shuttle. WSN have been successfully deployed to gather data in retrofit applications, which would otherwise have been prohibitively difficult or expensive [13]. Examples of these applications range from critical modules and robotics monitoring, astronaut health monitoring, in-flight structural health monitoring to general remote instrumentation and even early detection of magnetic storms.

5. Conclusion

The growing demand on air transport makes it extremely difficult for the flight industry to meet the stringent safety and security requirements of the aviation authorities without compromising the affordability of flight for the passengers. Paradoxically, the best way of reducing costs in the long term is to invest in the latest technological developments to be incorporated into the aircraft. As one of these novel technologies, WSAN can collect aircraft status information in real time, detecting failures earlier than is possible today, and react to these in a timely and accurate manner. They can be deployed, for instance, on aircraft wings to help the reduction of aerodynamic drag, thus reducing fuel consumption significantly, and helping the flight industry to improve the overall flight efficiency.

Recent research in this field is mainly based on the introduction of artificial airflow on the wings using SJA, which are static and proactive, to reduce the skin friction on the wings. In contrast, Active Aircraft uses WSAN to create virtual flap arrays on the wings, track the skin friction dynamically, and react to it in such a way that the artificial airflow can adapt itself to the changes in friction, both in magnitude as well as in location. The virtual arrays are organised into patches, with a number of sensors surrounding a single actuator in each patch. Communication within a patch is unidirectional from the sensors towards the actuator, thus presenting a convergecast pattern.

Like all active control applications and mission-critical systems, Active Aircraft has stringent performance requirements. The design considerations of the application and a high-level set of performance requirements for the underlying communication protocols we present reflect these requirements clearly. Our aim with this article is to describe a new approach to aircraft control technology, and raise some of the technological challenges of meeting the application requirements. Further research is necessary to test the suitability of the existing communication protocols to the conditions under which Active Aircraft operates, and to redesign these as necessary.

References

[1] European Commission, “EU Transport Research – Towards Future Air Transport,” available at http://ec.europa.eu/research/transport/transport_modes/aeronautics_en.cfm, last accessed September 26, 2009.

[2] Gad-el-Hak, M., *Flow Control: Passive, Active, and Reactive Flow Management*, Cambridge University Press, New York, 2000, pp. 150-188.

[3] Gilarranz, J.L., O.K. Rediniotis, "Compact, High-Power Synthetic Jet Actuators for Flow Separation Control," *Proceedings of the 39th Aerospace Sciences Meeting and Exhibit*, Reno, USA, January 8-11, 2001.

[4] Watson, M., A.J. Jaworski, N.J. Wood, “Application of Synthetic Jet Actuators for the Modification of the Characteristics of Separated Shear Layers on Slender Wings,” *Aeronautical Journal*, Vol. 111, No. 1122, pp. 519-529, August 2007.

[5] Halkes, G.P., K. Langendoen, “Crankshaft: An Energy-Efficient MAC Protocol for Dense Wireless Sensor Networks”, *Proceedings of the European Conference on Wireless Sensor Networks*, pp. 228-244, Delft, Netherlands, January 29-31, 2007.

[6] Demirkol, I., C. Ersoy, F. Alagöz, “MAC Protocols for Wireless Sensor Networks: A Survey”, *IEEE Communications Magazine*, Vol. 44, No. 4, pp. 115-121, April 2006.

[7] Akkaya, K., M. Younis, “A Survey on Routing Protocols for Wireless Sensor Networks,” *Ad Hoc Networks*, Vol. 3, No. 3, pp. 325-349, May 2005.

[8] Harman, R.M., “Wireless Solutions for Aircraft Condition Based Maintenance Systems”, *Proceedings of the IEEE Aerospace Conference*, pp. 6.2877-6.2886, Big Sky, USA, March 2002.

[9] Bai, H., M. Atiquzzaman, D. Lilja, “Wireless Sensor Network for Aircraft Health Monitoring”, *Proceedings of BROADNETS*, San Jose, USA, October 25-29, 2004.

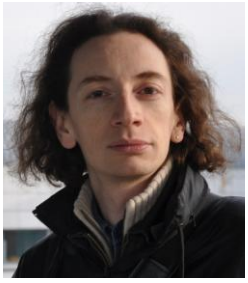
[10] Sampigethaya, K., M. Li, R. Poovendran, R. Robinson, “Secure Wireless Collection and Distribution of Commercial Airplane Health Data”, *Proceedings of the Digital Avionics Systems Conference*, Dallas, USA, October 21-25, 2007.

[11] Shang, B.-L., B.-F. Song, F. Chang, “New Sensor Technologies in Aircraft Structural Health Monitoring”, *Proceedings of the International Conference on Condition Monitoring and Diagnosis*, Beijing, China, April 21-24, 2008.

[12] Coelho, E.T., P. Carvalhal, M.J. Ferreira, L.F.F. Silva, H. Almeida, J.A. Afonso, C. Santos, “Distributed Sensing and Actuation over Bluetooth for Unmanned Air Vehicles”, *Proceedings of the IEEE International Conference on Robotics and Automation*, pp. 4363-4365, Orlando, USA, May 15-19, 2006.

[13] Clare, L.P., J.L. Gao, E.H. Jennings, C. Okino, “Communications Architecture for Space-Based Sensor Networks”, *Proceedings of the 2004 IEEE Aerospace Conference*, pp. 1251- 1268, Pasadena, USA, March 6-13, 2004.

Biographies



Kaan Bür *received his B.Sc. degree in control and computer engineering from Istanbul Technical University in 1995, and his M.Sc. as well as Ph.D. degrees in computer engineering from Boğaziçi University, Istanbul, in 1998 and 2006, respectively. From 2006 to 2007, he was a senior researcher at Faculty of Electrical Engineering and Computer Sciences, Berlin Technical University. From 2008 to 2009, he was a research associate at Department of Electronic and Electrical Engineering, University College London. Currently, he is a postdoctoral researcher at Department of Electrical and Information Technology, Lund University. His research interests include next generation networks, wireless sensor and mesh networks, mobile and vehicular ad hoc networks.*

Peter Omiyi *received the B.Eng. (Hons.) degree in electrical and electronic engineering from University of Manchester in 1996, and the Ph.D. degree in electrical and electronic engineering from University of Leeds in 2001. From 2003 to 2007, he was with International University of Bremen. From 2008 to 2009, he was a research associate at Department of Electronic and Electrical Engineering, University College London. Currently, he is a researcher at Faculty of Computing, Information Systems and Mathematics, Kingston University, London. His research interests include self-organised wireless networks and cognitive radio, with emphasis on decentralised medium access control and cross-layer optimisation. He holds several patents in the area of wireless communications.*

Yang Yang *received the B.Eng. and M.Eng. degrees in radio engineering from Southeast University, Nanjing, in 1996 and 1999, respectively, and the Ph.D. degree in information engineering from Chinese University of Hong Kong in 2002. Currently, he is a senior lecturer with Department of Electronic and Electrical Engineering, University College London, and the assistant director of Shanghai Research Center for Wireless Communications, Chinese Academy of Sciences. He served Department of Information Engineering at Chinese University of Hong Kong as an assistant professor from 2002 to 2003, and Department of Electronic and Computer Engineering at Brunel University, London, as a lecturer from 2003 to 2005. He published over 70 referred journal and conference papers covering a wide range of research areas, such as next generation mobile communications, wireless ad hoc, sensor and mesh networks, cross-layer algorithm design and performance evaluation, cooperative communications, cognitive radio, dynamic radio resource management, and medium access control.*