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TECHNICAL REPORT

colour inside

Information technology – Sensor network – Guidelines for design in the aeronautics industry: active air-flow control

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IEC Central Office
3, rue de Varembé
CH-1211 Geneva 20
Switzerland

Tel.: +41 22 919 02 11
Fax: +41 22 919 03 00
info@iec.ch
www.iec.ch

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INFORMATION TECHNOLOGY – SENSOR NETWORK – GUIDELINES FOR DESIGN IN THE AERONAUTICS INDUSTRY: ACTIVE AIR-FLOW CONTROL

FOREWORD

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ISO/IEC TR 22560, which is a Technical Report, has been prepared by subcommittee 41: Internet of Things and related technologies, of ISO/IEC joint technical committee 1: Information technology.

This Technical Report has been approved by vote of the member bodies, and the voting results may be obtained from the address given on the second title page.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

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INTRODUCTION

The number of wireless connections is growing exponentially around the world. Wireless communications are expanding to areas previously reluctant to use this type of technology. In the field of aeronautics, wireless intra-avionics applications are just recently gaining acceptance both in industrial and academic arenas. This late adoption is mainly because wireless transmissions have been conventionally associated with reliability and interference issues. Aeronautics applications on board aircraft are highly critical and therefore the inherent randomness of wireless technologies created lots of skepticism, particularly for sensing, monitoring and control of critical aeronautical subsystems. In addition, uncontrolled wireless transmissions can potentially create interference to other aeronautical subsystems, thus leading to malfunctions and unsafe operation. However, recent interference and reliability studies with state-of-the-art wireless standards suggest safe operation and thus the feasibility of a relatively new research area called wireless avionics intra-communications (WAICs). In the last few years, wireless technology has started to be used on board for systems that conventionally used only wire-line infrastructure (i.e., as replacement of cables). It is also being used for applications which are now only possible thanks to the wireless component (e.g., indoor localization, tracking and wireless power transfer). Examples of potential applications of wireless avionics intra-communications are the following: structure health monitoring, avionics bus communications, smoke sensors, interference monitoring, logistics, identification, replacing of cables, fuel tank sensors, automatic route control based on optimized fuel consumption and weather monitoring, automatic turbulence reduction or active air-flow control, EMI (electromagnetic interference) monitoring, and flexible wiring redundancy design.

The avionics industry will experience a wireless revolution in the years to come. The concept of “fly-by-wireless” opens several issues in design, configuration, security, spectrum management, and interference control. There are several advantages in the use of wireless technologies for the aeronautics industry. They permit reduction of cables in aircraft design, thus reducing weight. Reduction of weight also leads to increased payload capacity, longer ranges, faster speeds, and mainly savings in fuel consumption. The reduction of cables can also improve the flexibility of aircraft design (less manpower for designing complex cabling infrastructure). Additionally, wireless technologies can reach places of aircraft that are difficult to reach by cables, while being relatively immune to electrical cable malfunctions. Wireless technology also provides improved configuration and troubleshooting with over-the-air functionalities of modern radio standards.

This document presents the application of wireless sensor and actuator networks for the dynamic tracking and compensation of turbulent flows across the surface of aircraft. Turbulent flow formation and the associated skin drag effect are responsible for the inefficiency of airplane design and thus act as major factors in increased fuel consumption. The area of active air-flow control represents the convergence of several scientific fields such as: fluid mechanics, sensor networks, control theory, computational fluid dynamics, and actuator design. Due to the high speeds experienced by modern commercial aircraft, dense networks of sensors and actuators are necessary to accurately track the formation of turbulent flows and for counteracting their effects by convenient actuation policies. The use of wireless technologies in this field aims to facilitate the management of the information generated by the large number of sensors, and reduce the need for cables to interconnect all the nodes or groups of nodes (patches) in the network. Additionally, the use of the wireless components opens new issues in joint propagation and turbulence flow modelling. This document presents the design principles of active air-flow control systems using dense wireless/wired sensor networks compliant with the ISO sensor network reference architecture (SNRA). Standardized interfaces will help developers create smart cloud avionics applications that will improve fleet management, optimized route traffic, and computation of actuation profiles for different moments of an aircraft mission. This also lies within the context of future technological concepts such as Internet of things, Big Data, and cloud computing.

INFORMATION TECHNOLOGY – SENSOR NETWORK – GUIDELINES FOR DESIGN IN THE AERONAUTICS INDUSTRY: ACTIVE AIR-FLOW CONTROL

1 Scope

This document describes the concepts, issues, objectives, and requirements for the design of an active air-flow control (AFC) system for commercial aircraft based on a dense deployment of wired/wireless sensor and actuator networks. The objective of this AFC system is to track gradients of pressure across the surface of the fuselage of aircraft. This collected information will be used to activate a set of actuators that will attempt to reduce the skin drag effect produced by the separation between laminar and turbulent flows. This will be translated into increased lift-off forces, higher vehicle speeds, longer ranges, and reduced fuel consumption. The document focuses on the architecture design, module definition, statement of objectives, scalability analysis, system-level simulation, as well as networking and implementation issues using standardized interfaces and service-oriented middleware architectures. This document aims to serve as guideline on how to design wireless sensor and actuator networks compliant with ISO/IEC 29182.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO/IEC 29182-2:2013, *Information technology – Sensor networks: Sensor Network Reference Architecture (SNRA) – Part 2: Vocabulary and terminology*

ISO/IEC 29182-3:2014, *Information technology – Sensor networks: Sensor Network Reference Architecture (SNRA) – Part 3: Reference architecture views*

ISO/IEC 29182-4:2013, *Information technology – Sensor networks: Sensor Network Reference Architecture (SNRA) – Part 4: Entity models*

ISO/IEC 29182-5:2013, *Information technology – Sensor networks: Sensor Network Reference Architecture (SNRA) – Part 5: Interface definitions*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO/IEC 29182-2:2013 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org.obp

3.1
active air-flow control
AFC
ability to manipulate a flow field to improve efficiency or performance adding energy to the flow by an actuator and using a sensor or sensors to adjust, optimize, and turn on/off the actuation policy

3.2
ARINC 664
A664
standard that defines the electrical and protocol specifications (IEEE 802.3 and ARINC 664, Part 7) for the exchange of data between avionics subsystems [1][1]

3.3
boundary layer
BL
region in the immediate vicinity of a bounding surface in which the velocity of a flowing fluid increases rapidly from zero and approaches the velocity of the main stream [2]

3.4
boundary layer separation
detachment of a boundary layer from the surface into a broader wake [3], [4]

3.5
bubble

higher level abstraction of a heterogeneous wireless sensor network with different underlying technologies that enables semantic interoperability between them and with the external world using standardized interfaces and flexible middleware application program interfaces

3.6
computational fluid dynamics
CFD
art of using a computer to predict how gases and liquids flow [5]

3.7
drag
force acting opposite to the relative motion of any object moving with respect to a surrounding fluid [29]

3.8
fly-by-wireless
paradigm where avionics subsystems usually controlled or linked by means of cables will use now a wireless connection

3.9
fuselage
aircraft's main body section that holds crew and passengers or cargo [6]

3.10
laminar flow
flow regime that typically occurs at the lower velocities where the particles of fluid move entirely in straight lines even though the velocity with which the particles move along one line is not necessarily the same as along another line [7]

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[1] Numbers in square brackets refer to the Bibliography.

3.11
patch
array of sensors and actuators wired together with a central or distributed control scheme

3.12
Reynolds number
number that characterizes the relative importance of inertial and viscous forces in a flow

Note 1 to entry: It is important in determining the state of the flow, whether it is laminar or turbulent [7].

3.13
shear force
force acting on a substance in a direction perpendicular to the extension of the substance, acting in a direction to a planar cross section of a body [8]

3.14
skin friction drag
effect that arises from the friction of the fluid against the "skin" of the object that is moving through it [30]

3.15
synthetic jet actuator
type of actuator whose main effect is produced by the interactions of a train of vortices that are typically formed by alternating momentary ejection and suction of fluid across an orifice such that the net mass flux is zero [8]

3.16
turbulence
type of flow where the paths of individual particles of fluid are no longer everywhere straight (as in laminar flow) but are sinuous, intertwining and crossing one another in a disorderly manner so that a thorough mixing of fluid takes place [2]

3.17
viscosity
resistance of a fluid to a change in shape, or to the movement of neighbouring portions relative to one another [9]

3.18
wireless avionics intra-communications
type of wireless communications within an aircraft [10]

4 Symbols and abbreviated terms

4.1 Abbreviated terms

AFC	Active air-Flow Control
A664	ARINC 664
AGP	Accelerated Graphics Port
AOC	Airline Operation Control
ARINC	Aeronautical Radio INC.
BL	Boundary Layer
CAD	Computer Aided Design
CFD	Computational Fluid Dynamics
GS	Ground Systems
HLA	High-Level Architecture

L0	Level 0 of the aeronautical high-level architecture. Used to transport sensor reading via wireless/wireline infrastructure.
L1	Level 1 of the aeronautical high-level architecture. Used to interconnect several L0 WSNs.
L2	Level 2 of the aeronautical high-level architecture. Used to provide external access to the aeronautical WSN or bubble.
LNSE	Linear Navier-Stokes Equation
LSLI	Link-to-System Level Interface
MCDU	Multifunction Control Display Unit
MEMS	Micro-Electro-Mechanical Systems
SDBD	Single Dielectric Barrier Discharge
SFC	Specific Fuel Consumption
SJA	Synthetic Jet Actuator
UDP	User Datagram Protocol
VL	Virtual Link
WAIC	Wireless Avionics Intra Communications
ZNMF	Zero Net Mass Flux

4.2 Symbols

d	size of a patch
D	drag force
Δ_s	spacing between sensors (spatial sampling spacing)
f	sampling rate
g	gravitational constant
l	characteristic linear dimension of a fluid
L	lift force
$\frac{L}{D}$	lift-to-drag ratio
μ	dynamic viscosity of the fluid
N_a	number of actuators per patch
N_s	number of sensors per patch
N_p	number of patches per wireless sensor network gateway
p	pressure
ρ	density of the fluid
R	range
R_b	wireline nominal data rate
R_c	wireless nominal data rate
r_s	rate per sensor
Re	Reynolds number
$\mathbf{u}$	flow velocity vector
V	speed of the aircraft
ψ	kinematic viscosity of the fluid
$W_{initial}$	initial weight of the aircraft
W_{final}	final weight of the aircraft
ξ	data compression ratio inside a patch of sensors and actuators

5 Motivations for active air-flow control (AFC)

5.1 Skin drag

The environmental impact (CO_2 footprint) of the ever-increasing number of flights needs to be reduced. This can be achieved by means of new fuel sources, novel engine technologies and structures, advanced concepts of aircraft morphing (smart materials), improved aerodynamics, and improved air traffic management [34].

The reduction of fuel consumption is important for environmental protection purposes (reduced emissions) as well as for cost reduction. The potential for a 50 % reduction in fuel consumption within the next 15 years can be attained by using a combination of aerodynamic, engine, and structural improvements [11], as expressed by the well-known Breguet range equation:

$$R = \frac{V}{g \times SFC} \times \frac{L}{D} \times \ln\left(\frac{W_{\text{initial}}}{W_{\text{final}}}\right) \qquad (1)$$

where V is the velocity of the vehicle, L is the lift force, D is the drag force, SFC is the specific fuel consumption, $\ln(\cdot)$ is the natural logarithm function, g is the gravitational constant, W_{initial} is the initial weight of the aircraft and W_{final} is the final weight of the aircraft. By inspecting the expression in Formula (1) it becomes evident that technologies that reduce aircraft drag and the weight of an empty aircraft are crucial regardless of physical configuration. Aerodynamic drag is known to be one of the main factors contributing to increased aircraft fuel consumption. In [12], a study shows that for a long haul commercial aircraft (325 passengers) a combined reduction of 10 % in both skin friction and induced drag (i.e., the components that roughly contribute around 80 % to the total aerodynamic drag in such type of aircraft) may lead to a 15 % fuel consumption reduction. The drag breakdown of a commercial aircraft shows that skin friction drag and lift-induced drag constitute the two main sources of drag, approximately one half and one third, respectively, of the total drag for a typical long range aircraft in cruise conditions [12][13] (see Figure 1).

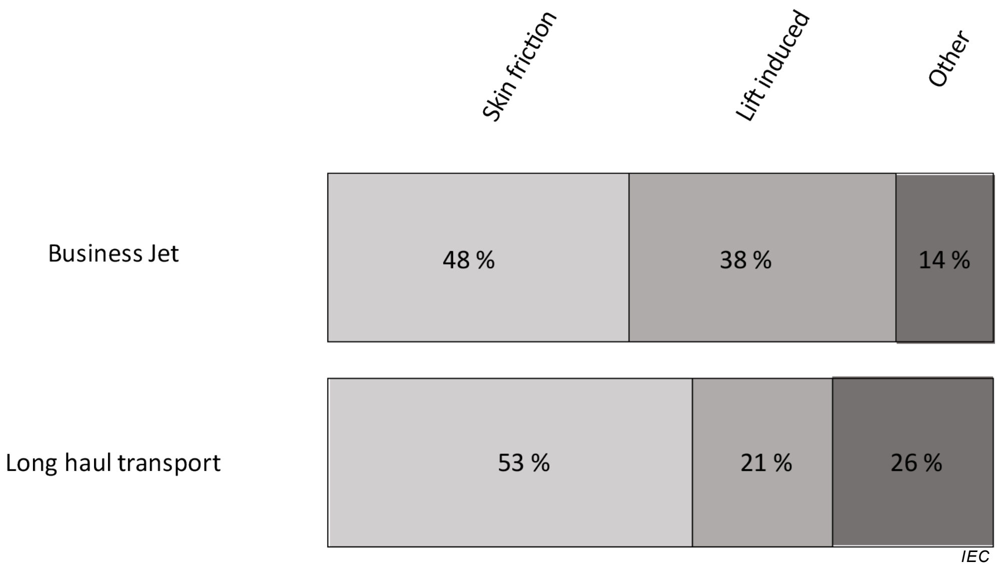

Figure 1 – Drag breakdown in commercial aircraft

Skin friction drag is therefore the main component of the aerodynamic drag. Skin friction arises from the friction of air against the skin of an aircraft in motion. The primary source of skin friction drag during a flight is the boundary layer separation. The boundary layer (BL) is the layer of air moving smoothly in the immediate vicinity of the aircraft (wing, fuselage, tail) where the flow velocity is lower than that of the free air stream. The proposal of the concept of boundary layer by Prandtl in [28] represented a turning point in the understanding of fluids flowing along the surface of solid objects and the conditions for turbulence formation (boundary layer separation). Inside the BL, viscosity effects are relevant and thus viscous forces dominate. As the flow develops along the surface, the smooth laminar flow is disturbed by the phenomenon of turbulence, which largely increases drag force (Figure 2). In a turbulent flow, viscous and shear forces attempt to counteract each other in a chaotic manner. In this transition, flow separation occurs due to a reversed flow at the surface, increasing drag (particularly pressure drag).

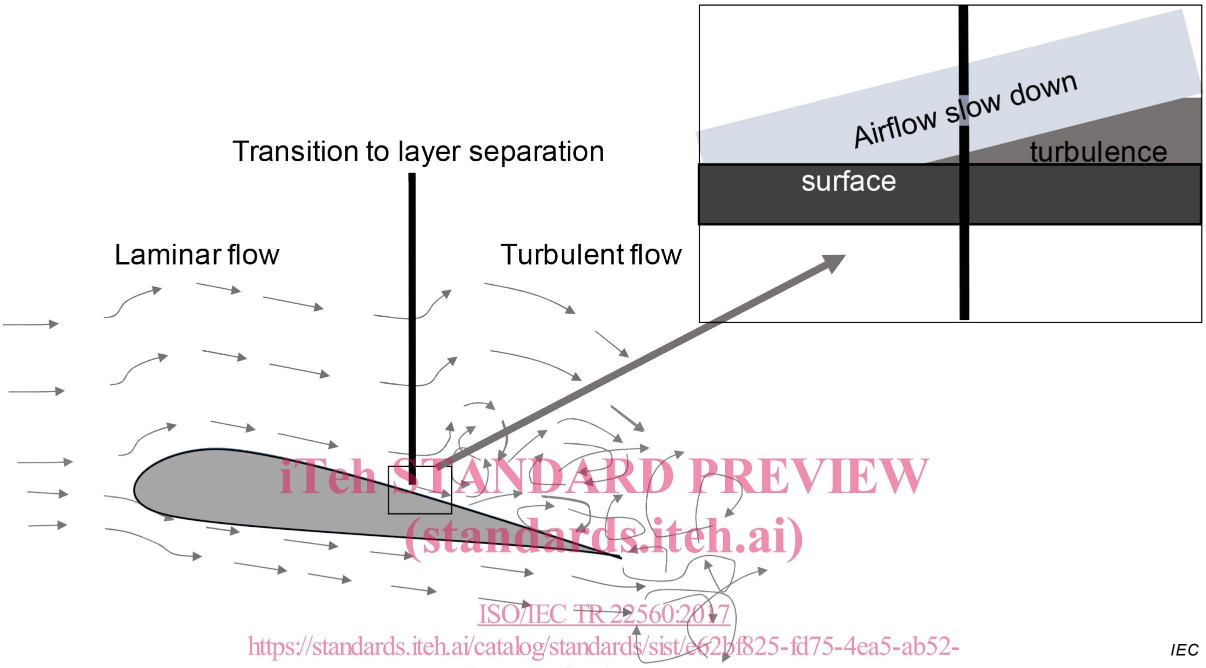

Figure 2 – Boundary layer (BL) transition exemplified with a wing profile

Both BL transition and separation can be controlled in order to reduce drag. Skin friction can be reduced by keeping the flow in the laminar regime, thus reducing the extent of turbulent flow over the air-foil. Preventing flow separation will improve lifting and reduce pressure drag.

5.2 Approaches for aircraft skin drag reduction

The position of the BL transition is affected by local flow disturbances that can be caused by several factors, such as: surface roughness, vibration, heat, air-stream turbulence, etc. There are various approaches to reduce turbulent skin friction, involving different mechanisms, such as:

- reducing turbulent friction drag through riblets;
- deformable active skin using smart materials (compliant walls), or by
- locally delaying the boundary layer transition using vortex generators, such as dimples, holes or synthetic jet actuators (SJAs).

In the case of SJAs, suction from the surface of the wing can be used to remove the low-energy air directly from the BL. Additional momentum (high-energy air) can be achieved in SJA solutions by generating stream wise vortices near the edge of the BL that re-energize the BL flow.

A recent research work in [14] uses SJAs located at key positions on the wing to continuously energize the BL and delay its separation. However, this approach does not use sensors to detect and trace the flow separation point, and is therefore static and proactive in nature. The efficiency of passive flow control is compromised and energy resources are wasted when there is no boundary layer separation or when it lies outside the optimal control field. For this reason, active air-flow control (AFC) approaches have been proposed that allow for a dynamic tracking of the BL via a network of sensors. By definition, AFC uses extra energy to control and manipulate flow conditions.

AFC is a multidisciplinary research field that integrates knowledge and exploits interactions on fluid mechanics, instability analysis, sensor and actuator design, and control systems, with the goal of improving aerodynamic performance. AFC has already been targeted by a number of research efforts (e.g., [11]–[14]). These works studied different aspects of AFC, including: energy consumption, efficiency, feedback control, delay, adjoint optimization, linear control, instability analysis, etc.

6 Objectives

6.1 General

Clause 6 provides a detailed explanation of the objectives of the AFC system based on dense wireless sensor and actuator networks.

6.2 Fuel efficiency

The proposed AFC system will increase fuel efficiency by reducing aircraft skin drag. It is expected that up to 25 % reduction of fuel consumption will be achieved in the next five years in the aeronautics industry. Fuel efficiency can be deduced from improvements of lift-to-drag ratio or simply lift-off forces.

6.3 Hybrid dense wired-wireless sensor and actuator networks

There is a need to design a dense network of patches of sensors/actuators wired together on the surface of fuselage of aircraft. Each patch represents a node in the architecture, communicating wirelessly with gateways located in different positions of the aircraft. This will be a hybrid network with wired and wireless features. Different types of sensor data with different statistics will be managed at different levels of the architecture, depending on latency and capacity restrictions.

6.4 Standardized and service oriented wireless sensor architecture

A standardized and service oriented architecture will be constructed for the AFC system, where the internal user lies in the command control unit of the aircraft and the external user is ground control operator. Standardized interfaces and architecture will help external users to create flexible smart avionics applications to improve fleet management and air traffic control. In this same line, service oriented architecture will enable the use of flexible middleware applications to develop high-level cloud avionics applications.

6.5 Re-/auto-/self-configuration

Develop advanced sensor and actuator nodes with re-/auto-/self-configuration features. The network of patches will be thus able to adapt to changing conditions based in different flight profiles, turbulence conditions, air traffic patterns, and both to internal and outer patch failures or incorrect measurements.

6.6 Communication protocols and scalability

Employ a wireless sensor and communication network for suppression of the turbulent flow. The dense wireless sensor network should be able to be used for different types of aircraft, and to increase the number of elements to allow for a full fuselage coverage in future deployments. A full scalability study should be conducted for the capacity, delay and other requirements of the intra-patch and inter-patch communication framework. This involves