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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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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]

[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:

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

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).

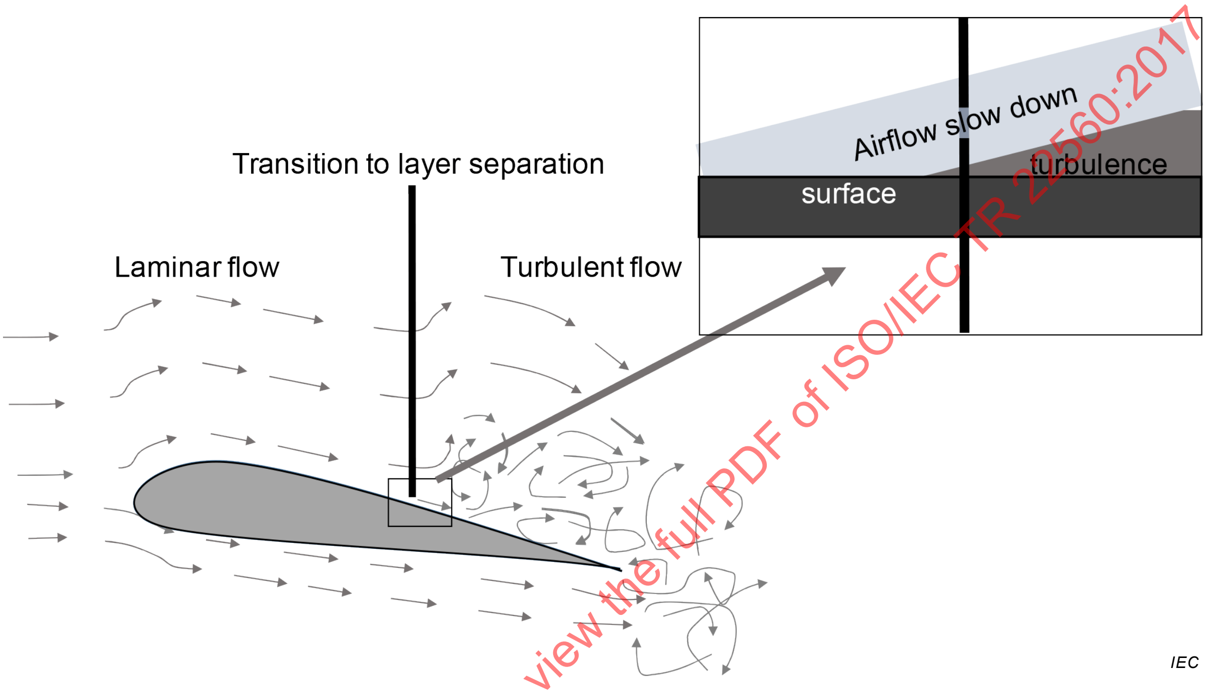


Figure 2 – Boundary layer (BL) transition exemplified with a wing profile

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 capacity calculation considering turbulence stability models, compression algorithms, intra-patch communication protocols, etc.

6.7 Smart actuation profiles and policies

Enable the use of actuation profiles optimized and managed by ground control in response to the collected sensor measurements. This implies the use of communication services to obtain data gathered by a fleet of airplanes and based on statistical analysis using cloud computing, to optimize actuation policies for different instants of a mission in different commercial routes.

6.8 High rate sensor measurement, synchronous operation and data compression

Obtain sensor measurements at high frequency and in synchronicity with each other, to be able to correlate sensor readings, especially from adjacent or closely located patches of sensors.

6.9 Troubleshooting and fail safe operation

The WSN also needs to deal with failures of sensors, and this can be approached by employing reliable data transmission, data delivery mechanisms, and also by employing data processing strategies that can deal with sensor failures or inaccuracies. Data redundancy can be used to estimate the position of the BL and recover potential errors across patches and across sensors. A malfunctioning sensor can detect erroneously the position of the BL, but using context and the feedback of adjacent sensors or patches, the measurement can be corrected or eliminated from the data aggregation process.

6.10 Enabling of wireless communication technologies in aeronautics industry

It is important to potentiate the use of wireless communication systems on board aircraft to enable the deployment, as soon as possible, of technologies like structural monitoring and AFC. This will reduce the time to market for commercial fly-by-wireless smart applications.

6.11 Integration of wireless technologies with the internal aeronautical communication systems

Wireless networks and sensor systems need to communicate and interact with the main data buses of the aircraft. This creates the challenge of protocol translation, gateway definition, etc.

6.12 Design of bidirectional wireless transmission protocols for relaying of aeronautical bus communication traffic

Design bidirectional bridges between different types of technologies. This is still the case if wireless technologies are used as the main data bus of the aircraft. Bidirectional transmission is necessary in modern aircraft communication systems. Therefore, the wireless transmission should support an abstraction of bidirectional traffic relaying, even if the underlying wireless technology is one-directional. This can be achieved by convenient scheduling design.

6.13 Matching of criticality levels of aeronautics industry

Ensure that different wireless networks, with different criticalities and different underlying technologies, will operate together without possibility of unreliable data delivery, reduced interference, and with adequate quality of service support.

6.14 Internetworking and protocol translation between wireless and wireline aeronautical networks

Bridge protocols and interfaces should be specified which respect the constraints of the different networks in the wireless and in the airline world. More specifically, the wireless network should support the operation of the internal aeronautics communication bus. In the case of ARINC 664 (A664), gateway definition should map the virtual links (VLs) of the A664 standard to the wireless sensor network.

7 System description

7.1 Overview of system operation

The main goal of the AFC system is to employ a dense wireless sensor-actuator and communication network for suppression of the turbulent flow and delaying the BL transition. The sensor network will detect the low-pressure region on the upper wing surface. The position of BL transition zone will be defined, selecting the appropriate actuators to be activated. At the same time, and based on the sensor values, the set of conditions for operation of the actuators (e.g., frequency, amplitude) will be calculated based on existing data (pre-set data). The selected actuators are activated to manage the turbulent flow on the wing surface. The data is stored. A new sensor reading is collected and the cycle is repeated. The stored data can be analysed to assess system operation during, for example, different flight profiles or moments (e.g., take-off, landing, and cruise) (see Figure 3).

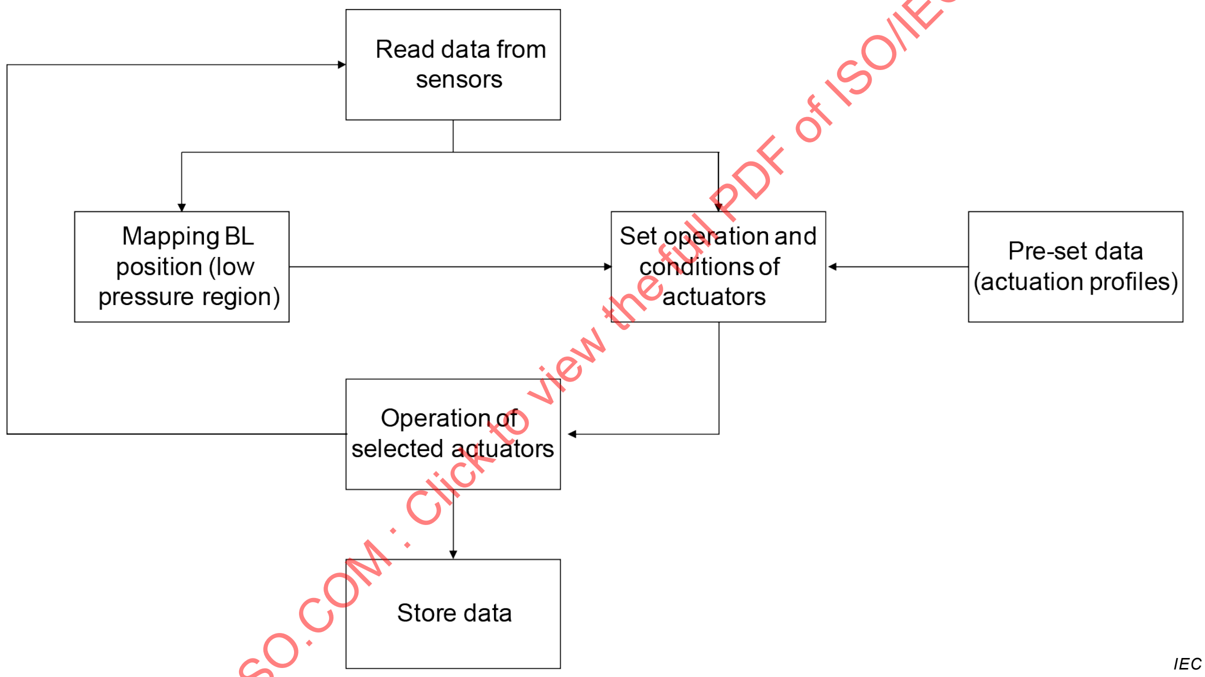


Figure 3 – Operation mode of the AFC system

Ground systems can interact with the sensor-actuator and communication network to get the data recorded during the flight and process this information to determine appropriate actuation plans and analyse the data of the whole fleet. Figure 4 depicts the architecture approach to tackle the AFC system.

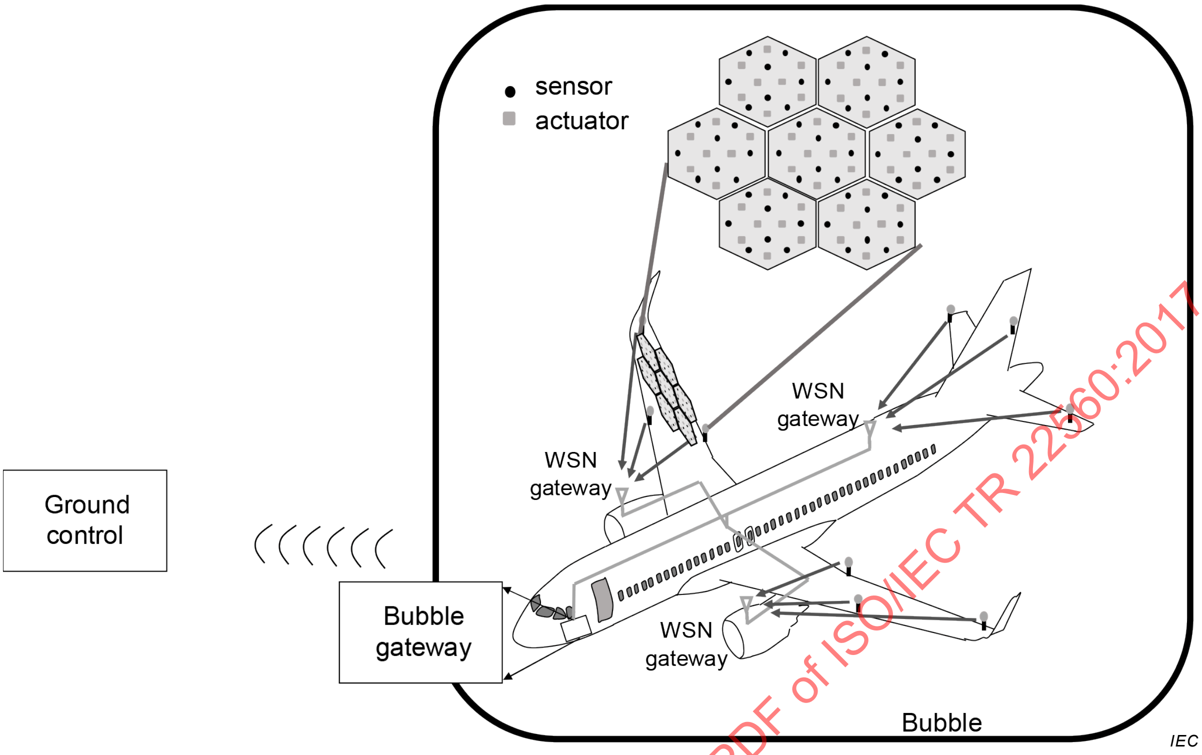


Figure 4 – Architecture of the AFC system

There are several challenges in the interconnectivity and how to achieve the desired objective in a dependable manner, whilst minimizing energy expenditure. The WSAN requires sensor measurements at high frequency and in a synchronous manner, to be able to correlate sensor readings, especially from sensors in close range. The WSAN also needs to deal with failures of sensors. This can be approached by employing reliable data transmission/delivery mechanisms, and data processing strategies that can deal with sensor failures. It is important to boost the use of wireless communication systems on board to enable the deployment, as soon as possible, of technologies like structural health monitoring (SHM) and AFC. To achieve this goal, these wireless networks and sensor systems need to communicate and interact with the main data buses of the aircraft. Hence, the specification of bidirectional bridges between different types of technologies is required. This is still the case if wireless technologies are used as the main data bus of the aircraft. Different wireless networks, with different delivery deadlines and different underlying technologies, should operate together without possibility of interference. Bridge protocols and interfaces should be specified considering the constraints of the different networks.

7.2 Patch design

The AFC system will consist of a set of polygonal patches, each patch with a regular grid/array of sensors and actuators. These patches will be located mainly on the surface of the wings of the aircraft, and potentially on other surfaces of the fuselage. The objective is to control the turbulence region across the aircraft and reduce losses. All the sensors and actuators inside a single patch will be wired together sharing a single communication and control point. The patches will communicate wirelessly either with a relay or with an access point located conveniently in the aircraft to ensure good communication with several patches. Each patch will be enabled with some sort of intelligence to provide management of all the sensors and actuators inside the patch and to provide convenient communication link with the sink and the control unit inside the WSN. The architecture of the AFC system is therefore a hybrid of wireless and wireline sensor network components. The information generated by each sensor will be collected by the control unit of each patch (node), which will provide some preliminary filtering, compression, fusion and aggregation functionalities. The refined information will be then relayed towards the control unit (gateway or relay node). Based on this collected information and based on different flight profiles, the AFC system will decide the type of actions to be performed by the set of actuators on each patch. Each of the flow control actuators is a piezoelectric device (SJA or flaperon). These actuators will allow the operator to change the boundary of the turbulence and thus help in counteracting the dragging effect in response to the measured information by the sensors and according to the current flight profile. The size and number of patches, as well as the number of sensors/actuators per patch, is expected to be optimized using a simulator. These parameters are expected to be a function of the accuracy of the AFC system, the range of the wireless technology selected, and the data rate of the wireless sensor nodes. All sensor/actuators nodes will be powered via cables. The patch will be provided with some power saving features too. For example, when sensor information or actuation is not required from some patches, they can be powered down until they need to be used again.

The configuration proposed for the AFC system constitutes a hybrid design with wired and wireless components. This allows the AFC system to combine the main attributes and benefits of both technologies. The number of sensors for this application is expected to be large, more than in common WSNs, being deployed over a relatively small area. This creates the issue of interference, provided each individual sensor is enabled with a dedicated wireless connection. To address this issue, the AFC system uses an architecture where groups of sensors wired together form a patch that will act as a single radio transmitter. Each patch will be provided with smart self-configuration and control. Figure 5 shows the possible embodiment of a regular design of sensor and actuators inside a patch. Each patch will have a radio transceiver and a control unit with some intelligence. This node will be in charge of the processing operations inside the patch, including functions such as filtering, data fusion, and aggregation of information to be sent towards the wireless gateway.

By using patches of wired sensors and actuators, and enabling wireless technology for communication between patches, the complexity and management of the dense sensor network becomes more flexible, scalable, and commercially more attractive as it can be implemented on different aircraft models with different geometries and configurations.

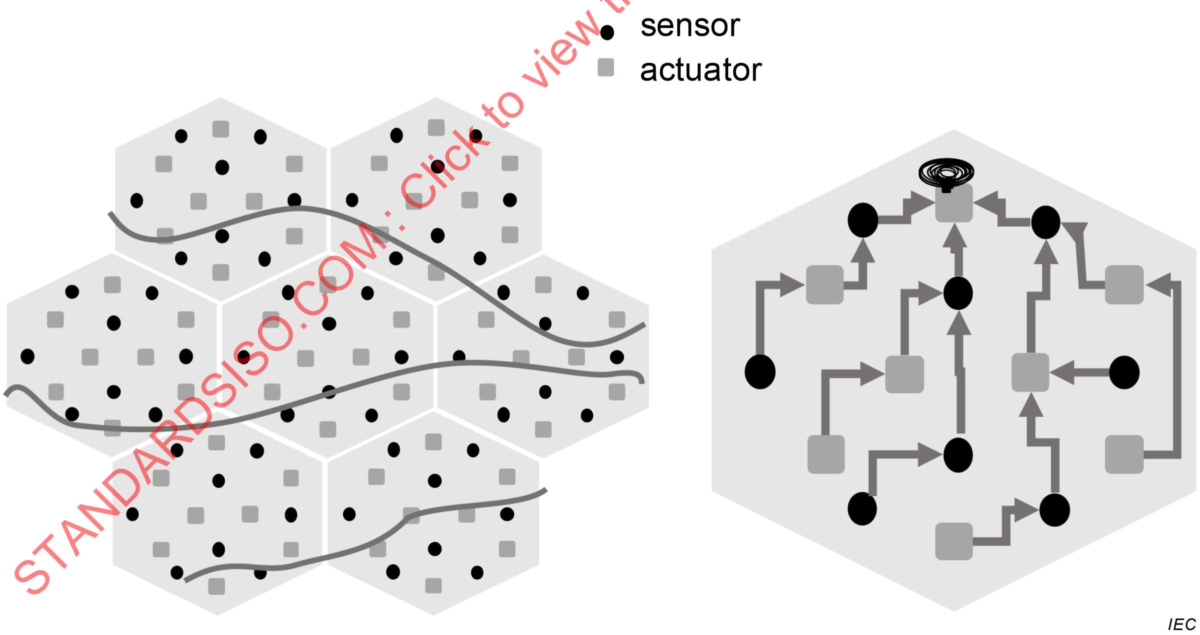


Figure 5 – Array(s) of patches of sensors/actuators

7.3 Internal aeronautics network

Another important part of the AFC system is the interconnection of the wireless network with the avionics internal communication systems as shown in Figure 6. The proposed solution should ensure the reliable relaying of traffic from/to the wireless sensor/actuator network to the internal avionics network under different quality of service constraints. In general, the ARINC 664 (A664) network has more stringent quality of service requirements, therefore the solution should include an appropriate scheduler that will ensure that these quality of service constraints of the A664 traffic are met or conveniently addressed when transported to/from the wireless domain.

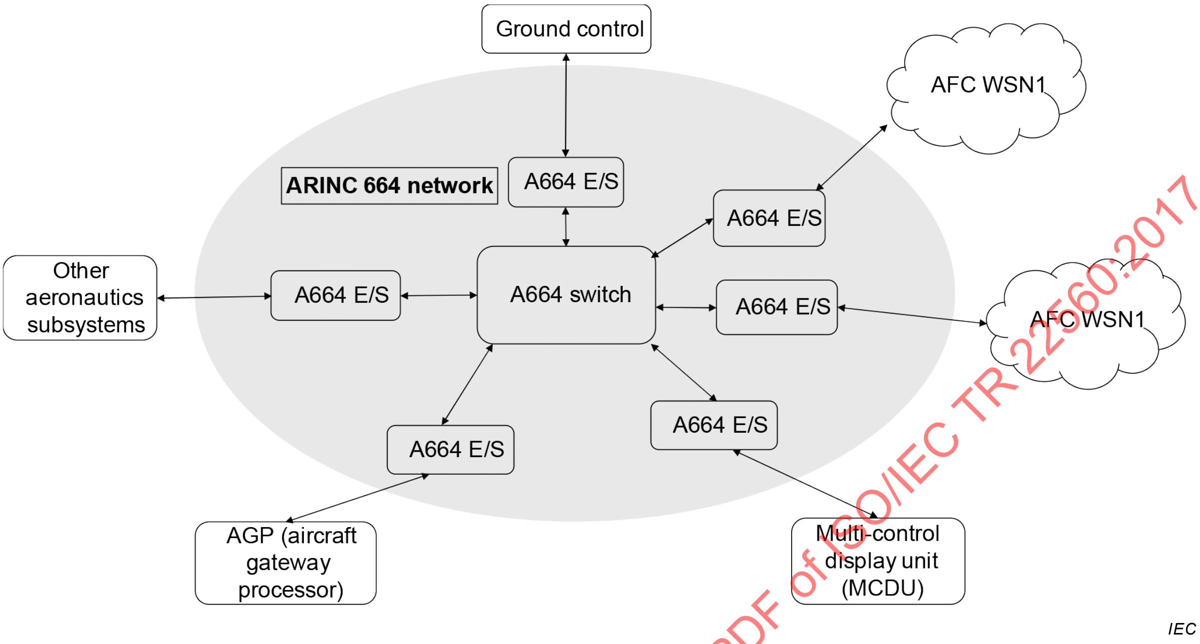


Figure 6 – Interaction with internal avionics networks

8 Micro-sensors and actuators

8.1 Micro-sensors

Sensors for AFC applications need to be easy to install, non-invasive for not disturbing the flow, and able to detect and estimate the near-wall flow state, e.g., by means of measuring local pressure or shear stress. Techniques to measure wall shear stress can be categorized as: thermal, mechanical and optical. A particularly attractive solution is the micro hot-film shear stress sensor which has been conventionally associated with the field of MEMS (micro-electro-mechanical systems). There are some issues related to this kind of sensors regarding heat loss to the substrate, problems in measuring the flow direction, and consequently in resolving vortices orientation. However, many advances have been made over the last few years, and good results have been reported. For example, in [16] a MEMS sensor array with forty sensors was constructed over an area of 70×70 mm, with a sensor spacing of 1,5 mm.

Recently, two consecutive European projects called AEROMEMS and AEROMEMS II (advanced aerodynamic flow control using MEMS) [17], addressed the integration and cost/benefit assessments of MEMS flow separation control technology used to improve the performance of wing high-lift systems, engine nacelles, and turbo-machinery components. These projects addressed further development of prototype MEMS flow sensors and actuators of the previous EU funded projects. The objective was to improve efficiency and address the issues of robustness associated with engineering integration. In this context, the authors in [18] presented a double hot-wire sensor, which was called hybrid AeroMEMS sensor array. It was a combination of a flexible printed circuit board (PCB) and a number of MEMS double hot-wires, single wires in different sensors setups, with each sensor featuring an area of 800×600 µm. As an improvement over the single hot-wire, the double sensor was able to measure the flow direction. Tests were conducted in a wind tunnel demonstrating its applicability in determining flow speed and directions, showing efficiency in determining the boundary layer separation. By means of numerical optimization it was shown that the thermal field pattern increases the frequency response. Under the same project, but with another approach, the authors in [18] designed a high-resolution AeroMEMS sensor array for pressure measurements. The sensor cell is composed of a diaphragm with piezo-resistor located at the edges of the cell. Measurements were based on the longitudinal and transversal piezo-resistive effect. A 2,5 × 4,5 × 0,3 mm chip was constructed, composed of a 900 × 900 µm diaphragm with a satisfactory sensitivity and frequency response of up to 160 kHz. An array of 13 sensors was mounted on a cylinder in a wind tunnel, so as to compare the measurements with the theoretical expected values. The results led to the construction of a fully functional and reliable sensor. Schober et al. [20] have developed a MEMS surface fence sensor for skin friction measurements. The fence equipped with piezo-resistors is 300 µm high and 5 mm long which sticks out of the wall, with a resolution of the wall shear stress of 0,02 Pa, and a temporal resolution up to 1 kHz. Another approach is the micro-pillar sensor for wall-shear-stress measurement. Preceded by Engel et al. [21], Chen et al. [22] reported that water flows as low as 1 mm/s can be measured with their MEMS pillar sensor using doped-silicon piezo-resistive strain gauges and an epoxy pillar.

8.2 Actuators

The field of AFC has experienced an explosive growth over the last few years. This demand has been reflected on a wide variety of actuators that exist today. This is evidence of the importance and challenges associated with actuators design. Actuators are transducers that convert an electrical signal to a desired physical quantity. The active air-flow actuators modify a flow by means of electronically controlled disturbances, which can be generated in many ways. 8.2 presents the state-of-the-art overview and an analysis of the possible application of the different types of actuator in the AFC system, mainly based on spatial and temporal requirements.

There are various types of actuators used in flow control applications with different operational principles. Cattafesta and Sheplak [23] suggested a classification in which the actuators are organized based on their functionality, as illustrated in Figure 7. A common type of actuator is fluidic, which is based on the fluid injection and suction from/to the environment. Periodic excitation (injection/suction) is preferable rather than steady flow because the flow can be excited at natural (intrinsic) frequencies of the instabilities in the separating flow.

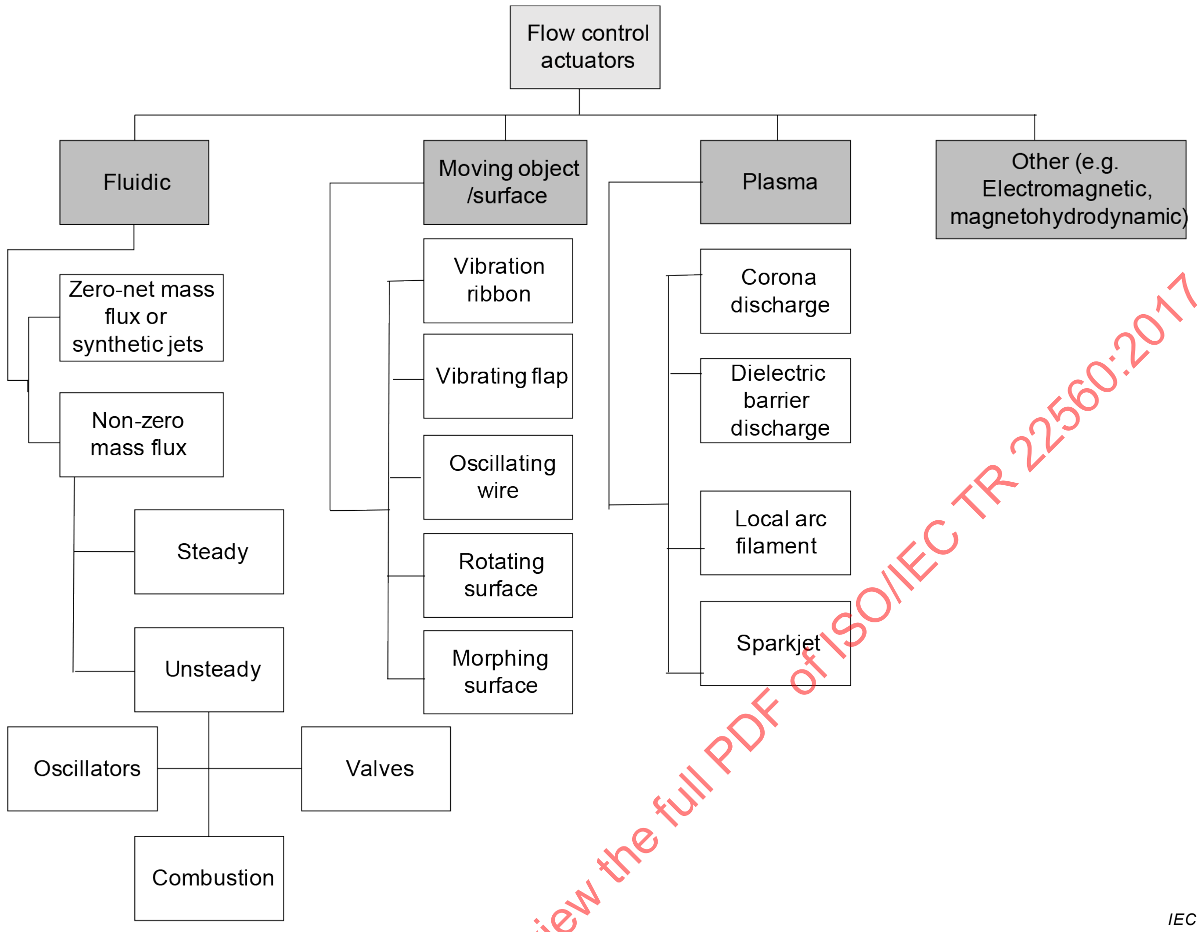


Figure 7 – Flow control actuators classified by function [22]

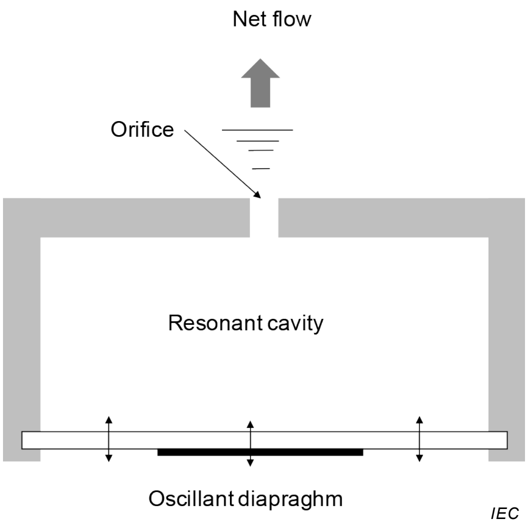
Two other kinds of actuators are derived from this main concept:

- Zero-net mass-flux (ZNMF), also called synthetic jet actuators (SJAs). In these actuators, the amount of air blown out and sucked in is the same; and
- Non-zero mass-flux.

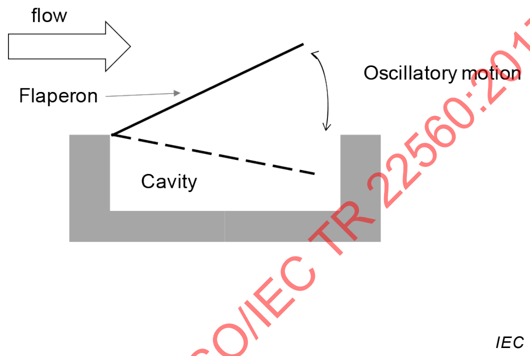
The first type of actuator is generally based on a diaphragm which ingests or/and expels fluid (air) through an orifice/slot in an oscillatory manner, using only the working fluid with no external mass source/sink. Non-zero mass-flux devices, on the other hand, can also ingest or expel fluid from/to a source/sink. They can operate in a steady or unsteady state, like pulsed jets, natural fluidic oscillators, and combustion-driven devices. They can range in scale from conventional macro-scale to micro-jets.

Typical fluidic devices are based on piezoelectric or electrodynamics diaphragm. The diaphragm oscillates about its equilibrium position, alternately expelling/ingesting fluid from/into its cavity. SJAs have been applied in various flow control applications, including separation control and jet vectoring [23]. Diez and Dahm [26] have proposed a dense array of SJAs and obtained a flat frequency response up to 10 kHz with a relatively low driving voltage of (15–20) V.

Other type of actuator involves a solid body explicitly invading the boundary layer. This explicit invasion aims to generate changes on the local flow motion. This can be performed by vibrating flaps, time-periodic motion of a surface mounted diaphragm, an oscillator wire, rotating surface elements and morphing surfaces. These actuators can take various forms, among which the most common are the piezoelectric composite flaps and electro active dimples. Suzuki et al. [27] developed magnetic flap actuators with a copper coil on polyimide film for jet mixing control. They obtained a 0,4 mm tip displacement at a current of 1 A and a resonant frequency of 270 Hz. The two types of actuator discussed here are illustrated in Figure 8.



a)



b)

Figure 8 – Flow control actuators: a) SJA; b) flaperon

The last class here considered is given by solid-state actuators, also called plasma actuators. These actuators have gained popularity because of the lack of moving mechanical elements and because of their short response time. The most popular one is the single dielectric barrier discharge (SDBD) plasma actuator, which consists of an asymmetric pair of electrodes separated by a dielectric material. An AC waveform with voltages between 1 kV and 30 kV and frequencies from 50 kHz to 20 kHz is supplied to the exposed electrode. This results in an asymmetric electric field which ionizes the air molecules, forming locally cold plasma. The accelerated charged particles transfer momentum to the surrounding gas, adjacent to the surface, via collisions with neutral particles, causing the desired flow disturbance. The work in [27] presents how to implement two different flow control techniques for skin friction that achieved a 45 % reduction. Experimental results were obtained using different modifications to the near-wall structures depending on the control technique.

9 High-level architecture for aeronautical WSANs

9.1 Bubble concept

The bubble concept is used as a high-level abstraction of a wireless sensor or group of wireless sensor networks with standardized interfaces. A bubble can be therefore a set of WSNs with different underlying technologies but a common standard interface for external and internal users. A bubble will be compliant with ISO/IEC 29182. The concept of a bubble is used to improve interoperability and development of higher level abstraction applications for smart cities and Internet of things. The concept of bubble has been developed in the context of the European ARTEMIS project called DEWI (dependable embedded wireless infrastructure) [34]. Since a bubble can contain one or more WSNs, three hierarchical levels for networking and interoperability are automatically defined. These levels are defined in 9.2.

9.2 Layered model

The high-level architecture (HLA) of the AFC system consists of three hierarchical levels or layers on top of ISO/IEC 29182 (see Figure 9).

Level 0 (L0) is the communication technology/architecture inside a specific wireless sensor network (intra-WSN). Each WSN can have a different Level 0 technology. Several WSNs can be hosted by one L0/L1 or aeronautical gateway.

Level 1 (L1) is the communication technology/architecture used to connect several WSNs to a L1/L2 gateway. L1 represents the existing aeronautical internal communication network. Several L0 WSANs can be connected to the same L1 technology. Therefore, L1 should also be in charge of resource allocation and conflict resolution between multiple L0 WSANs. The use of L1 technology in the architecture provides great flexibility in the design of industrial WSNs. L1 is associated with the existing infrastructure in different industrial domains, and therefore in some cases it is a real time or highly critical network. This has profound implications in system design of industrial WSNs. There will be a need to provide convenient protocol adaptation between L0 and L1 technologies. This is of particular importance in the aeronautics industry because of the criticality of traffic and sensor information on board an aircraft.

Level 2 (L2) is the communication technology towards the external world. It provides a common external access to multiple aeronautical WSANs. This technology should be a standard for all aeronautical WSANs so that clients get a flexible and standardized access to the data generated by the network of sensors and actuators of multiple aircraft. L2 will be mainly resident in ground control for airline operators to manage and monitor different aspects of a fleet.

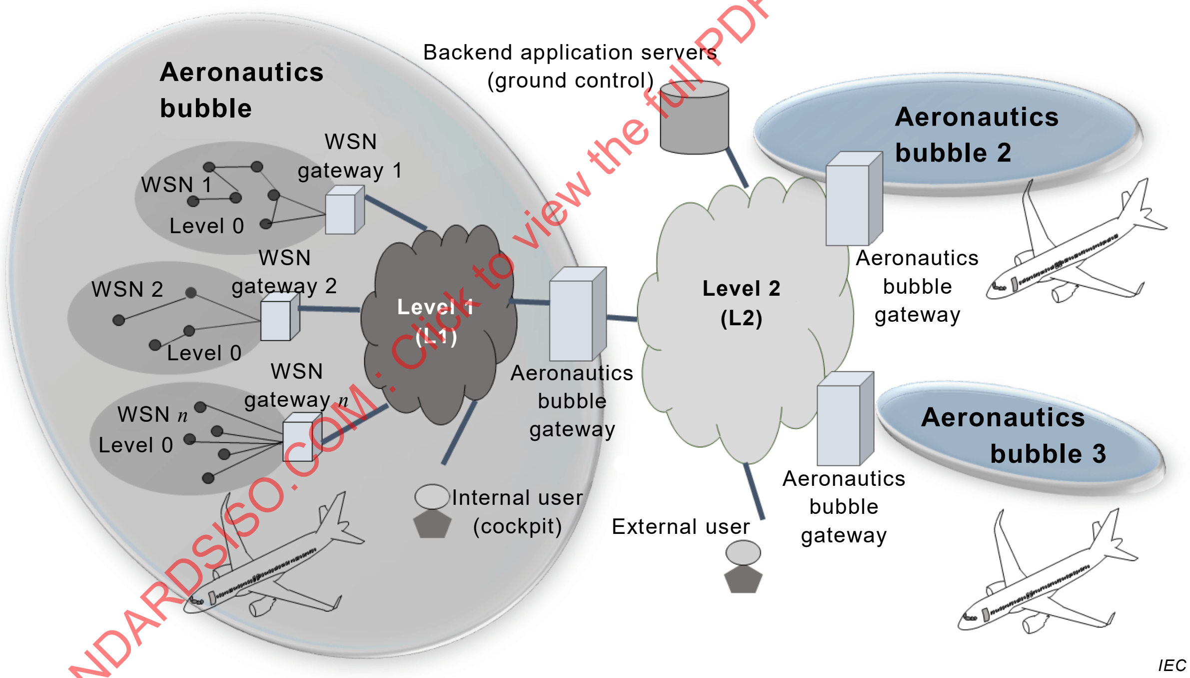


Figure 9 – HLA mapping AFC system

Table 1 shows the mapping of the interfaces of AFC system described in this document to the layered model of the HLA.

Table 1 – Mapping of AFC system to the HLA layered model

HLA element	Definition
WSN Service for user	Tracking of turbulent flow and actuation (internal user)
Actuation policy update (external user)	
Level 0 WSN – used term	AFC (active air-flow control) bubble
WSN mode – used term	N/A
WSN physical layer technology	IEEE 802.15.4
WSN higher layer protocol(s) / middleware	ZigBee®[a]
Level 0 gateway	ZigBee AP
Level 1 Network – Physical layer technology	ARINC 664
Level 1 Network – higher layer protocol(s) or middleware	UDP/IP
Internal User (if applicable)	Pilot
Aeronautics gateway – used term	Bubble gateway
Level 2 Network higher layer protocol(s)	Private IP network ground control
Potential other aeronautical WSNs	Monitoring of other parameters of the aircraft
External User (if applicable)	Ground control

[a] ZigBee is the trademark of a product supplied by the ZigBee Alliance. This information is given for the convenience of users of this document and does not constitute an endorsement by IEC of the product named.

The AFC system uses a hybrid combination of wired and wireless elements to form patches of sensors and actuators. This is the Level 0 (L0). A set of wireless sensor gateways will be placed in different parts of the aircraft to collect information from different patches. The WSN gateways will be connected to the internal aeronautics network of the aircraft, which is an ARINC 664. ARINC 664 is a highly reliable deterministic version of Ethernet technology. This is Level 1 (L1) of the architecture in reference to the HLA. Therefore, the bubble gateway will be used to relay information between ground control and the aircraft. This means that one L1 entity is envisioned to operate in each aircraft. Ground control or the operational centre of the airliner will host the technology for Level 2 (private IP network).

9.3 Mapping to ISO/IEC 29182 Sensor Networks Reference Architecture (SNRA)

The AFC system is compliant with the reference architecture specified in ISO/IEC 29182-2 to ISO/IEC 29182-5. Figures 10 to 13 provide the mapping of the aeronautical use case to this reference architecture. In each figure, the elements that are shaded in blue colour are the elements of the ISO/IEC 29182 architecture that will be used in the AFC system. Elements not shaded are not included in the AFC architecture.

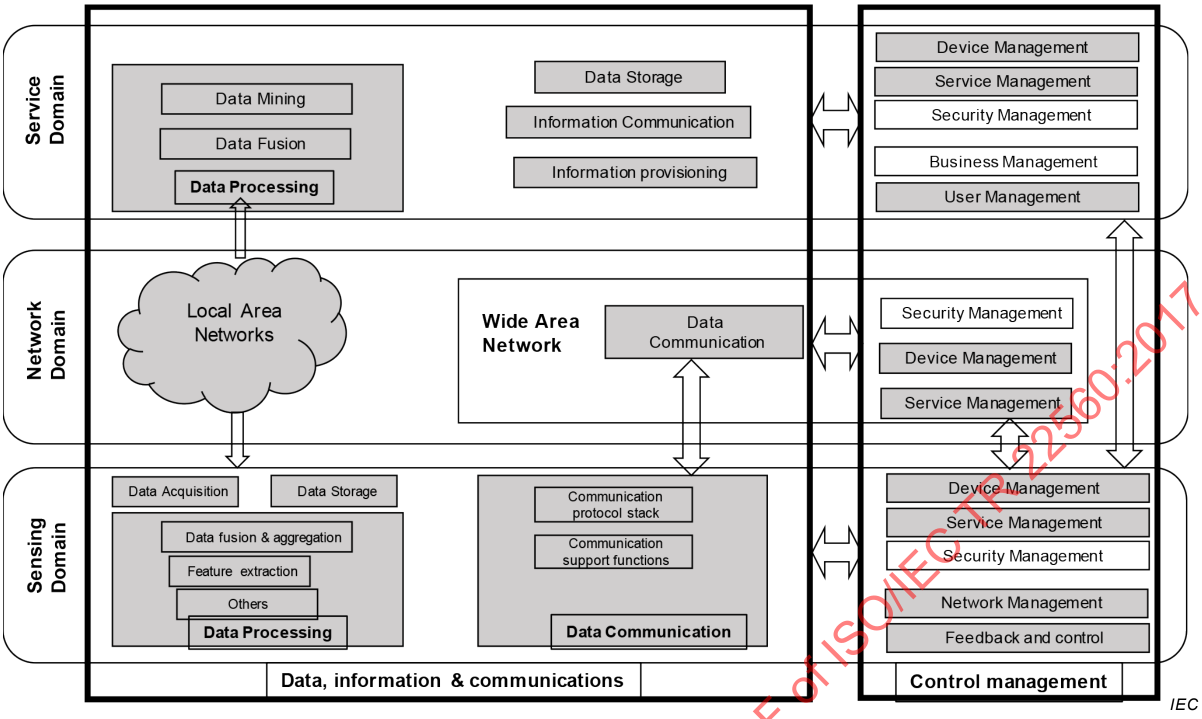


Figure 10 – Mapping AFC system to the ISO/IEC 29182 view

Figure 10 shows the domain architecture view of the reference architecture, while Figure 11 provides the functional perspective. In general, most of the functionalities and interfaces of ISO/IEC 29182 will be implemented in the AFC system. The exception lies in the security and privacy domain, mainly because it is not the main objective of the AFC system. Energy harvesting is not currently considered in the AFC system, as well as collaborative information processing and self-localization

Regarding the sensor physical architecture depicted in Figure 12, it is expected that the AFC architecture will implement all of the functionalities and entities. An array of sensors and actuators will be wired together forming a patch. This array of sensors and actuators will use one single communication and data processing module. Therefore, Figure 12 can be modified to include a complete wired network of sensors and actuators instead of a single element.

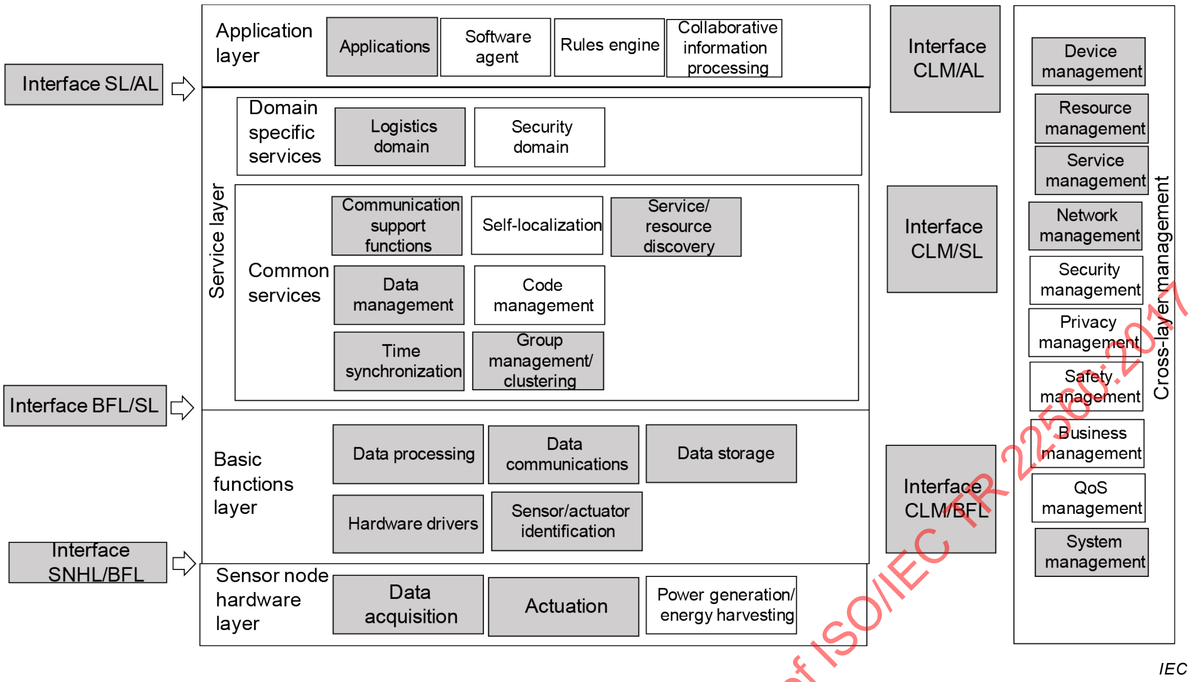


Figure 11 – Mapping AFC system to the ISO/IEC 29182 layered reference architecture view

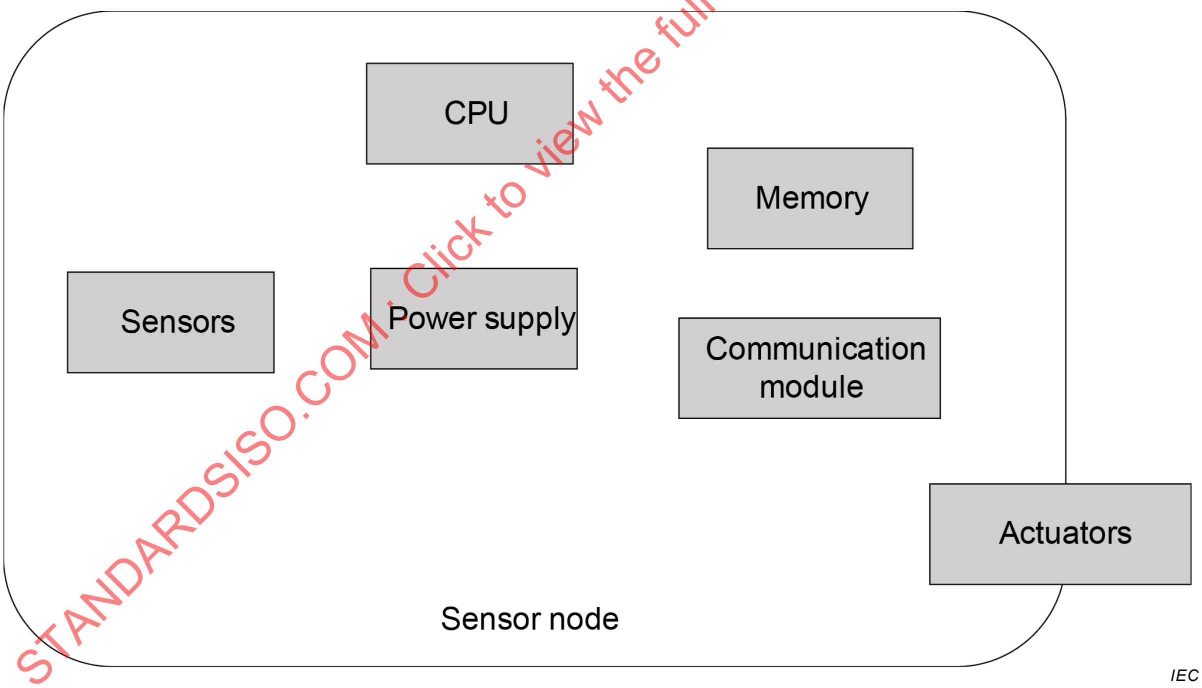


Figure 12 – Mapping AFC system to the ISO/IEC 29182 sensor node reference architecture

The reference architecture physical and interface view displayed in Figure 13 illustrates that most of the entities are relevant for the two use cases except for the interfaces of the service provider. In the AFC system, service providers are not under consideration, mainly because the processing and actuation control loops occur inside the AFC system.

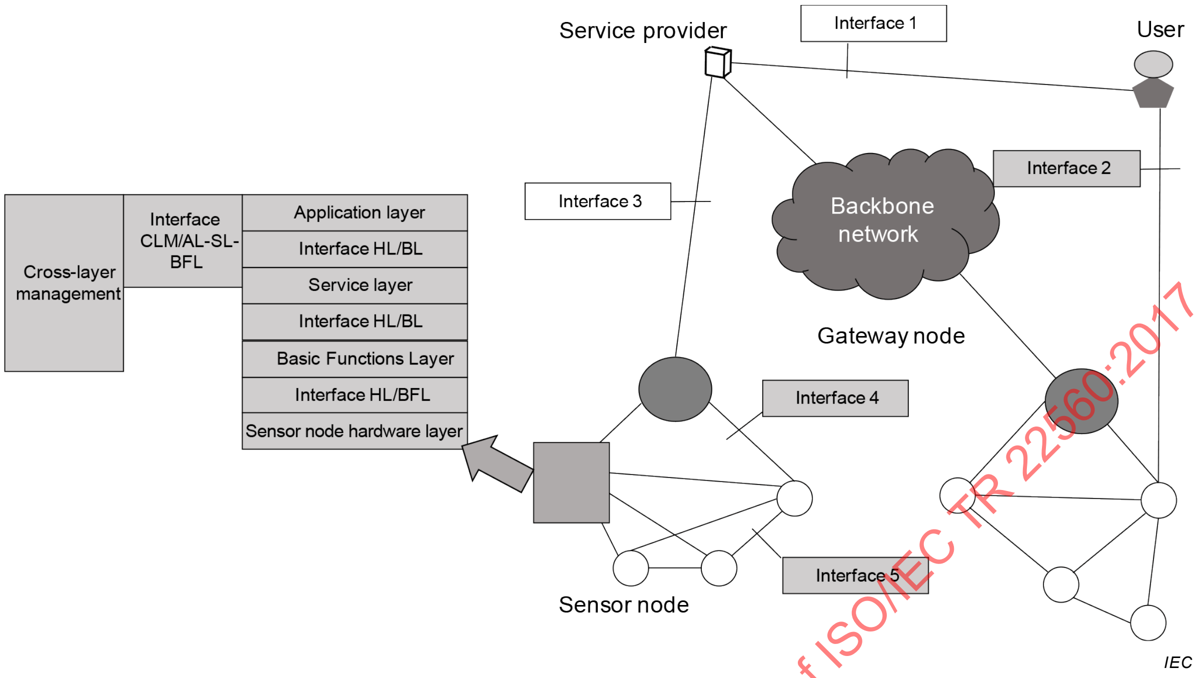


Figure 13 – Mapping AFC system to the ISO/IEC 29182 physical reference architecture

Table 2 and Table 3 provide the mapping of the AFC system to ISO/IEC 29182. Table 2 provides the mapping of all functionalities of ISO/IEC 29182 to the different physical entities in the network. Table 2 shows the relevant intersections for ISO/IEC 29182 and for the AFC system. Table 3 shows the mapping of the different interfaces of this use case to the different interfaces defined in ISO/IEC 29182. Note that the interface to service providers is not used in the AFC system.

Table 2 – Mapping of AFC architecture to ISO/IEC 29182 entity and functional models

				Physical entities										
				Sensor nodes							Other networks			
				Sensors	Actuators	Communications module	Processor	Memory	Power supply	Gateways (L0,L1,and L2)	Access networks	Backbone network	Service providers	Users (internal and external)
Functional entities	Sensor node hardware layer		Data acquisition	x										
			Actuation		x									
			Power generation / energy harvesting						•					
	Basic functions		Data processing	x			x	x						
			Data communications			x				x	x	x	•	x
			Data storage					x					•	x
			Hardware drivers	x	x		x							
			Sensor/actuator identification	x	x		x							
	Service layer	Common services	Communications support functions			x	x	x		x	x	x	•	x
			Self-localization	•		•	•							
			Service/resource discovery			x							•	x
			Data management				x	x					•	x
			Code management				x	x		x			•	x
			Time synchronization			x	x						•	x
			Group management/clustering			x	x	x					•	
			Domain specific services				x						•	
	Application layer		Applications				x						•	
			Software agent				x			x			•	x
			Rules engine				x						•	x
			Collaborative information processing	x	☼		X	X					•	X
	Cross-layer management		Device management	x	x	x				x				
			Resource management	x	x	x	x	x					•	x
			Service management										•	x
			Network management			x	x	x					•	x
			Security management			•	•	•		•			•	•
			Privacy management											
			Safety management											
			Business management				x	x					x	x
			QoS management	x	x	x	x	x		x			x	x
			System monitoring	x	x	x	x	x	x					

x ISO/IEC 29182 and AFC

• ISO/IEC 29182, not AFC

☼ not ISO, AFC

Table 3 – Mapping of AFC system to ISO/IEC 29182 interface model

	Interface 1 (service provider to/from user)	**Interface 2 (sensor node to/from user)**	**Interface 3 (gateway to/from service provider)**	**Interface 4 (sensor node to/from gateway)**	**Interface 5 (sensor node to/from sensor node)**
Application layer to/from application layer	N/A	ZigBee stack	N/A	ZigBee stack/A664 or Ethernet	N/A
Service layer to/from service layer	N/A	ZigBee stack	N/A	ZigBee stack/A664 or Ethernet	ZigBee stack
Basic functions layer to/from basic functions layer	N/A	IEEE 802.15.4	N/A	IEEE 802.15.4/ A664 or Ethernet	IEEE 802.15.4
Sensor node hardware layer to/from sensor node hardware layer	N/A	IEEE 802.15.4	N/A	IEEE 802.15.4/ A664 or Ethernet	IEEE 802.15.4

10 Requirements for AFC design

10.1 Sensing and actuation

10.1.1 BL position detection and space-time resolution

10.1.1.1 Description

The sensor system should be able to detect the position of the BL with good temporal and spatial resolution for an appropriate actuation control.

10.1.1.2 Rationale

The position of the BL needs to be tracked with a good resolution in space and time. This will enable an efficient actuation flow control. This resolution will be established according to the performance of the actuating system, the distribution of actuators, and the drag reduction effect. This will define the number of sensors/actuators to be used. The right number of sensors and actuators should be found so that the BL can be efficiently tracked/detected and subsequently controlled (actuation).

10.1.2 Efficient flow control actuation

10.1.2.1 Description

The flow control actuators should be able to suppress the flow turbulence in its vicinity modifying the BL.

10.1.2.2 Rationale

The turbulence flow is to be reduced by the flow control actuators in order to reduce skin drag. The accuracy of the flow control system depends, in first instance, on the accuracy and resolution of the BL tracking, which in turn depends on the number of sensors. Secondly, the number of actuators and the actuation policy should be able to react to the sensed information and modify conveniently, accurately and efficiently the BL. This defines also the number of actuators to be used and the required latency of the whole AFC system, including the network side.

10.1.3 Patch intra- and inter-communication

10.1.3.1 Description

A patch comprises a set of sensors and actuators, a wireless communication node and sensor data pre-processing functions. Each patch of sensors/actuators should have a communication point for secure wireless transmission of sensors data. Each patch should also ensure the correct management, scheduling and connection with the internal sensors and actuators.

10.1.3.2 Rationale

The high number of sensors and actuators required for the particular scenario of AFC system demands a hybrid network architecture: a set of sensors and actuators are wired together forming a patch. Each patch has a control and communication node that will oversee the internal management, scheduling and intra-communication between the sensors and actuators of the patch. Additionally, it will be in charge of sensor data pre-processing (compressing) and also to connect wirelessly to a relay or sink node.

10.1.4 Patch sensor data pre-processing, fusion, management and storage

10.1.4.1 Description

The sensor data collected by each patch should be pre-processed, filtered, and refined locally at the controller unit of each patch. This will allow for some compression, and therefore reduction of the data rate for each patch. Some of the data will be stored for redundancy and error correction features.

10.1.4.2 Rationale

The high number of sensors and actuators envisioned for the AFC system demands a new architectural and data processing approach. Sensors and actuators are grouped and wired together in patches. These patches are connected via wireless link to gateways or relays. The data collected by each patch needs to be pre-processed, refined, or filtered so as to use as low as possible wireless bandwidth. The large number of patches demands that each patch uses low bandwidths. Sensor data may be stored for purposes of redundancy, error control, context information management, and for self-organization features.

10.1.5 Patch configuration, redundancy, and organization

10.1.5.1 Description

Each patch of sensors/actuators will be provided with some smart configuration and organization capabilities. Each patch will be semi-autonomous and can help other patches or organize their data or operations for actuating control. Patch organization will be used for redundancy in case of sensor/actuator failure.

10.1.5.2 Rationale

The AFC system demands a high density of sensors and actuators. This means that not all the data can be processed, controlled or managed centrally. Each patch of sensors and actuators therefore will be provided with some kind of intelligence, to reduce control and data traffic and also to reduce the requirements on the wireless and wired network. This will help for creating a faster response for the AFC system in addition to redundancy or self-healing features, as well as a better organization between patches and thus less interference in the system. Patches need to optimize as much as possible their operation, complexity, weight, power consumption and data rate. Therefore, software and hardware co-design are expected to help patches reach these objectives

The system should be able to provide real time information (with a reduced time latency) for the activation of actuators. Real time data is relevant for good operation of the system.

10.1.6 Sensors synchronicity

10.1.6.1 Description

The data from sensors may be acquired in a synchronous manner.

10.1.6.2 Rationale

The synchronicity on sensor data reading is relevant mainly for a correct positioning of the BL and if the readings are to be correlated. This may be especially relevant from sensors in close proximity, e.g., in the same patch.

10.1.7 Low power sensor-actuator (patch) consumption

10.1.7.1 Description

The power consumption of each patch should be low.

10.1.7.2 Rationale

The power consumption of each patch should be as low as possible in order to minimize energy expenditure. Actuation and sensing policies can be designed so that when a set of sensor or actuators are not required (according to the flight profiles) they can be powered off to save energy. The wireless network can be also designed so that the access points or sinks are conveniently located across the aircraft and the link with every patch is good enough to reduce power consumption.

10.1.8 Patch data rate and traffic constraints

10.1.8.1 Description

The data rate for wireless connection of each patch will be low to save bandwidth, reduce conflict with other patches or on-board systems and to improve overall throughput/delay.

10.1.8.2 Rationale

The high number of sensors and actuators in the AFC system and the need to track accurately and with good resolution the boundary layer across different surfaces of the aircraft means that a lot of sensors readings as well as actuator control messages need to be transported. Some current wireless technologies might not be able to support such traffic requirement. The proposed patches will pre-process sensor data to compress, filter and refine the relevant information. This will allow a reduction of data rates to be transported over wireless. The remaining question will be how many sensors and actuators per patch can be controlled and compressed and the expected data rate per patch to support a good wireless networking in a scenario with potentially tens or hundreds of patches.

10.1.9 Patch low complexity

10.1.9.1 Description

Each patch is expected to have low complexity, which means that sensors and actuators will be managed in a very similar way. Actuators will perform perhaps the same action to reduce complexity of the actuation profile.

10.1.9.2 Rationale

The operation of actuators will be the same inside each patch in order to reduce complexity.

10.2 Sensor network communications

10.2.1 Interference

10.2.1.1 Description

Resilience to external interferences and low interference to on-board wireless systems.

10.2.1.2 Rationale

Due to the 'open' nature of wireless communications, the WSNs may be exposed to various interferences. This requires that the employed wireless links should demonstrate satisfying performance of immunity to moderate interferences. There are many existing on-board wireless systems in modern aircrafts, including both critical and non-essential wireless systems. The wireless links employed by the WSNs should not cause noticeable interference to these existing on-board wireless systems.

10.2.2 Wireless range and connectivity

10.2.2.1 Description

All patches on the aircraft need to have a reliable wireless link with a relay or with the L0 gateway.

10.2.2.2 Rationale

A wireless sensor network on an aircraft should be carefully designed so that all sensors (in our case patches) have a reliable connection with the next hop destination of the network. This range of reliable transmission is also upper bounded by the potential interference to other on-board systems.

10.3 Aeronautical network and on-board systems

10.3.1 Full-duplex communications

10.3.1.1 Description

The on-board application should be able to establish full-duplex communication over the wireless network.

10.3.1.2 Rationale

The internal avionics network is a highly reliable and full duplex communication channel. Therefore, the wireless network that will be designed to interact with this underlying network should support the same type of service. The scheduler is an important part to ensure that full duplex connection is achieved over a wireless link, which is generically less reliable and half duplex in principle.

10.3.2 Compatibility with avionics internal network (ARINC 664)

10.3.2.1 Description

The on-board application should provide a bridge between the wireless network and the ARINC 664 network (A/C data bus interaction). The bridge and wireless should support periodic and aperiodic data messages. The application should be agnostic to the underlying communication network architecture, i.e. be able to communicate transparently from the internal network of the aircraft. The router should provide a wireless interface. The bridge should provide a dual redundant AFDX end system interface. The router should be configurable enabling the mapping between VL and addresses in the wireless network. The bridge should convert the wireless network protocol and map it to virtual links. The bridge should support the timing constraints of the ARINC 664 network.

10.3.2.2 Rationale

The AFC system should interact with the internal avionics network just as any other sensor on the aircraft would do. In order to support this interaction, the bridge or gateway should mimic the operations and protocol procedures of the internal network and transform the instructions into the AFC wireless sensor network. This protocol translation needs to be achieved with as much transparency as possible to ensure backwards compatibility, quality of service provisioning, and ultimately safe and reliable integration.

10.3.3 AFC interface

10.3.3.1 Description

The application should be able to receive data from the AFC platform for turbulence control. The application should receive status report from the AFC system, and it should send the flight phase/mode to the AFC system.

10.3.3.2 Rationale

The middleware layer should provide a convenient interface with the underlying AFC system, and support application development and connectivity to the internal avionics network. The AFC network will transport sensor measurements to the internal avionics network that will proceed to relay them over to ground control for the selection of a convenient actuation plan.

10.3.4 GS interface

10.3.4.1 Description

Ground systems (GS) can interact with the system. GS will provide sensor data fusion and context information for actuation (flight profiles).

10.3.4.2 Rationale

The smart patches should communicate with GS. This includes for instance the data recorded and processed during the flight in order to determine appropriate actuation plans and analyse the data of the fleet. Sensor data and flight profile data should be used to control the action of the flow control actuators. The system should be able to collect the sensor readings and help in refining actuation policies during different moments of a flight profile. This interaction is key for the efficiency of the AFC system and for enabling higher level applications such as air traffic management.

11 Testing platform and prototype development

Prototypes for AFC systems are developed and tested in a representative environment that can reproduce turbulent conditions on wing mockup sections. Wind tunnels are therefore necessary for testing AFC systems. The design of a wind tunnel involves several aspects that have to be considered for the success of the testing. The main variable of a wind tunnel is the air flow speed achieved. This speed depends on the fan used, the type of wind tunnel constructed and its dimensions. Open- or closed-return tunnels can be used. The air flow speed will determine the type of turbulence created over a section of a wing under test. Wing sections should also be selected to match the conditions and dimensions of the wind tunnel. A wing profile should be selected that can achieve a reasonable lift and drag conditions in the range considered for the testing. NACA (National Advisory Committee for Aeronautics) profiles are widely used for building wing sections for testing of AFC systems. Sensors should be selected to detect the envisioned changes of pressure. Most importantly actuators should be designed to produce the required vortexes or flow changes that will be translated into some form of detectable gains. Optimization of the placement of sensors and actuators as well as the actuation policies should be conducted using some type of CFD simulation. Finally, the testing platform should consider a method to measure either directly or indirectly the gains of the active air-flow control systems. Load cells or pressure sensors can provide information on the gains of the AFC systems. Figure 14 shows a prototype implementation of the AFC system in a wind tunnel platform. The figure shows wind tunnels used for testing, the software interface to measure pressure values across the surface of a wing section, and the wing section itself with mounted pressure sensors and different types of actuators.

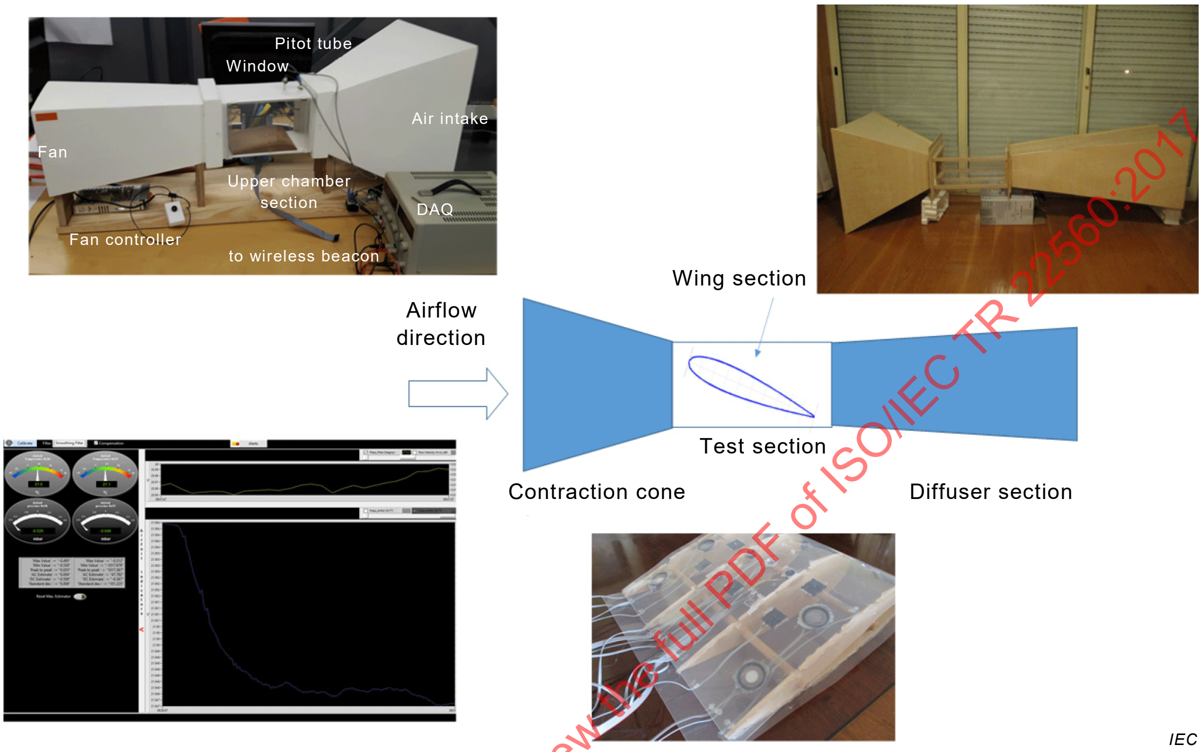


Figure 14 – Prototype implementation AFC system

12 Scalability

The number of sensor nodes per patch is denoted by N_s and the number of actuators by N_a. Different actuation policies are possible. For example, amplitude and frequency of the piezoelectric material in the actuator can be adjusted according to different measurements of turbulence or according to a model that predicts the need of different levels of actuation inside the turbulent flow area. Under the worst-case scenario, the density of sensing and actuation should be as small as 0,1 mm at 100 kHz (denoted here by Δ_s and f respectively). On the other hand, in the best-case scenario, we are looking at sensing density in the order of 1 cm at 1 kHz or even 10 cm at 100 Hz to track the medium term statistics of the boundary separation layer. More details of the model for turbulent flows used in this document can be found in Annex A.

To obtain the number of sensors and actuators per patch, let us now focus on the data transport algorithm inside the patch. There are many possible combinations for algorithms inside the patch. For simplicity, we will consider a bus configuration that will allow us to obtain closed-form expressions for the number of required nodes in a patch. For other transport algorithms and network configurations such as Manhattan grid and multi-hop data transport, in general simulation in NS-3 will be required. Let us now consider Ethernet as the baseband transport technology inside a patch with R_b = 100 Gbps capacity. In the worst-case scenario, the sensing data rate per sensor, considering 8-bit representation, approximately of 800 kbps plus overhead resulting in a rough estimate of r_s = 1 Mbps. This means each patch can potentially host up to100 000 sensors, which in a rectangular patch means approximately 300 sensors per side. This is obviously optimistic, mainly because of potential collisions or transmission errors in the physical and MAC layers. Using a 50 % margin (ξ = 0,5), one patch could host 50 000 sensors using 100 Gbps Ethernet, or 50 for 100 Mbps Ethernet. In the

Ethernet version implemented by ARINC 664 of the aeronautical internal communication network, 100 Mbps is the maximum data rate. The above calculation can be expressed mathematically as follows:

$$N_s = \frac{\xi R_b}{r_s}$$

Where ξ is the compression rate, R_b is the rate of the bus technology, and r_s = 10f is the rate per sensor. To conclude, we can say that in the worst-case scenario, approximately 50 sensor nodes can be hosted per patch using ARINC 664 Ethernet in shared bus configuration. Other data transmission configurations can improve this figure at the expense of further processing per sensor node or delay in processing multi-hop configurations. It is also possible to enable local processing per sensor node and only transport compressed information inside the patch. The physical size of the patch can be obtained as follows:

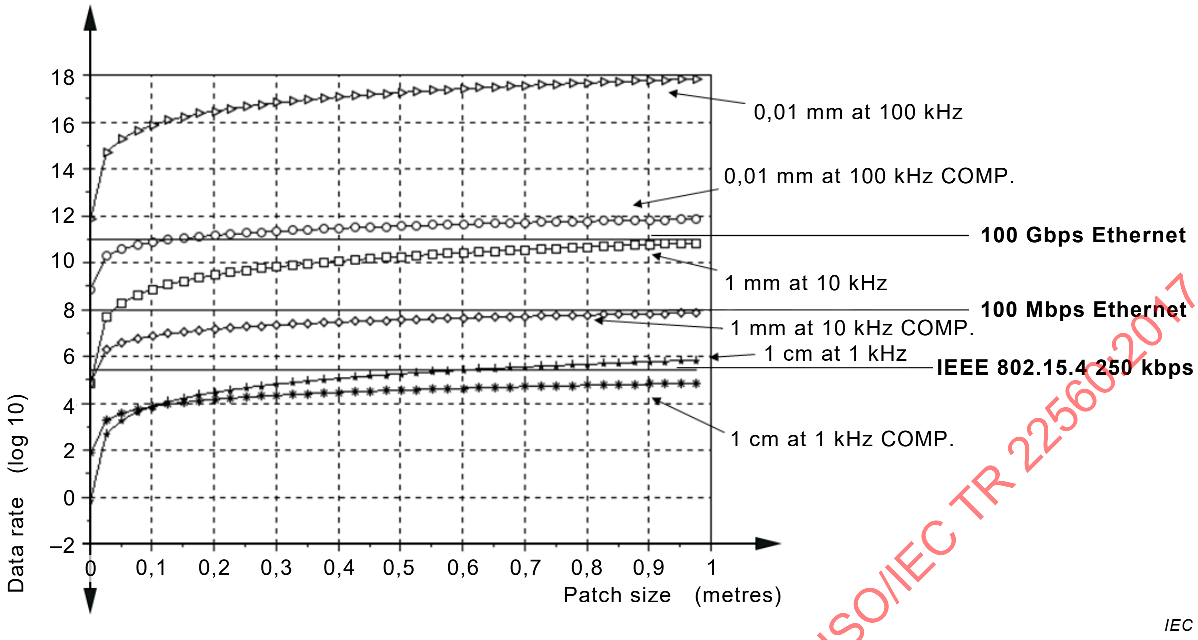
$$l = \Delta_s \sqrt{N_s}$$

Note that the sizes of the patch in the worst-case scenario boils down to only 2,2 cm when using 100 Gbps Ethernet or 0,07 cm with 100 Mbps Ethernet. These sizes of a patch are too small. This means that inside the patch only a limited number of sensors can be wired together when dealing with the micro scale turbulent component. In the best-case scenario, the estimate data rate number goes up to 10 kbps or 1 kbps. Using 100 Mbps Ethernet and following the lines of the previous calculation, the estimated number of sensors per patch increases to 5 000 and 50 000, respectively. However, the size of the patch will be mainly limited by the wireless technology used for patch to sink node communication. Assuming IEEE 802.15.4 technology for a patch with a capacity of 250 kbps, the maximum number of nodes per patch could be obtained as 12 or 125 when dealing with the small-scale statistics of turbulence (our best-case scenario). However, this calculation assumes that there is only one patch in the network. Considering time-slot operation of IEEE 802.15.4, N_p = 7 patches can transmit simultaneously sharing the overall data rate. Therefore, the number of nodes per patch can go down to only 2 or 13, respectively. On the other hand, if Wi-Fi technology is employed with 600 Mbps, this number can go up to 60 or 600 assuming heavy losses by collisions. This can be expressed as follows:

$$N_s = \frac{\xi R_c}{N_p r_s}$$

where N_p is the number of patches per radio channel and R_c is the data rate per radio channel. Regarding the size of the patch with IEEE 802.15.4, the size can be as small as 1,3 cm or 42 cm per side. This latter result corresponds to the case with 10 cm at 100 Hz sensing rates. Also note that it is possible to use more sensors for inside patch processing and then compress the information (subsample) for communication with the wireless network. This offers several possibilities for realization of the patch and the deployment of the aeronautics AFC system.

An attractive option to improve scalability of the AFC system is the use of compression algorithms. It can be proved that when using boundary detection algorithms, the number of sensor readings to be transmitted per time interval reduces from N_s to $\sqrt{N_s}$. This means that the size of the patch can be considerably improved or the capacity of the wireless transmission technology considerably relaxed. Figure 15 shows the data rate requirements for different sampling rates for the turbulent flow considering no compression and compression. In the same graphs the data rate of the main wireline and wireless standards for wireless local and sensor networks are also displayed. It can be observed that the wireless component (IEEE 802.15.4) can only handle levels of turbulence within the range of 1 cm at 1 kHz, while 100 Gbps Ethernet could potentially deal with the worst-case scenario for avionics of 0,001 mm at 100 kHz using compression and boundary detection algorithms.



COMP. = compression

Figure 15 – Data rate vs patch size.

Further analysis of scalability and other aspects of the system level evaluation of the AFC system can be found in Annex B.

Annex A
(informative)

System level simulation

A.1 Architecture of the simulator and module description

A.1.1 Fluid modelling domain

The architecture of a simulator should closely follow the architecture of the system to be simulated. The simulator architecture is shown in Figure A.1. The first block of the simulator is the computational fluid dynamics (CFD) block which is in charge of the simulation of the turbulence boundary layer separation and the effects of actuators. The CFD block provides the information for the network of sensors that will be able to track the boundary layer that separates the laminar from turbulent flows. This information will be therefore our traffic model input for the wireless sensor network and the patch configuration. It is not possible to conduct simultaneous CFD and WSAN simulations due to complexity constraints. Therefore, the results of CFD should be computed off-line and then imported into the simulator via an interface model. Different interface and instability models have been implemented in the simulator to obtain the statistics of the separation processes across the surface of a wing. The boundary layer process is considered as a bi-dimensional space-time stochastic process that can be modelled as a random envelope with spatial and temporal correlation properties. These correlation statistics depend on the speed of the fluid, and the angle of attack. The simulator also has the option of using its own instability model based on the concept of propagator matrix commonly used to model instability in flows. All interface models have been implemented for the whole duration of an aircraft mission considering different angles of attack. Therefore, the simulator can reproduce the flight conditions of different aircraft, which is an attractive aspect for applications of traffic and fleet management in the context of smart aeronautics applications.

A.1.2 Sensor and actuators configuration: patches

The network of sensors and actuators is organized in patches. The number of sensors and actuators per patch, as well as their spacing and positions within the patch, can be configured in the simulator. This also defines the size of the patch and the number of patches used to cover a designated area over the fuselage of the aircraft. The simulation tool includes options for the internal network of sensors and actuators. It enables the design of an internal network of processors communicating readings through the wired network. This configuration allows us to study the real-time properties of the intra-patch communication and evaluate delay, packet error performance, etc. An important aspect included in the intra-patch network design is the implementation of compression algorithms that allow for reducing the requirements of communication bandwidth to transport sensor readings inside the patch. The simulation tool includes an option to implement compression algorithms, particularly those related to boundary detection. The main interest for the network of sensors is the detection of the boundary layer separation between laminar and turbulent flows. The idea of the network of patches is that different levels of the network can process different levels of statistics of the air flow. This means that faster statistic of turbulent flow can be only processed inside the patch and potentially at each sensor and actuator elements. Slower changes of turbulent flow can be relayed from each patch towards the internal aeronautics network, where the statistics of all the patches of the aircraft can be monitored and processed. Fine tuning of the actuation profile can be performed for the network of patches on board each aircraft. one more level of processing can be enabled at ground control, where the measurements of a complete fleet of aircraft can be processed and analysed.

A.1.3 Wing design, aircraft configuration, and propagation modelling

The simulator also allows for different aircraft configurations of different sizes and more importantly different wing profiles using the NACA series. A user of the simulator can configure the coefficients of symmetrical and non-symmetrical NACA airfoil profiles. The configuration of the aircraft also defines the propagation electromagnetic model, which is crucial for the evaluation of the wireless component. Several propagation models have been included in the simulator, including our own calculated metrics using ray tracing algorithm. The simulator can also include other propagation models and fit the best or mixture of the best models according to the scenario considered. The channel model is used for the evaluation of the physical (PHY) layer of the wireless technology in use, which is related to the modulation format, encoding, frame definition, power and signal processing operations. The PHY-layer should interact with the simulator mainly via a compression model. The joint simulation of PHY and upper layers is in general too complex to be included dynamically in the same software tool. PHY-layer simulations are usually carried out off-line and the results are imported into the main simulator via look-up-tables or link-to-system-level interface (LSLI) compression models.

A.1.4 Radio resource management

The core of the simulator is the block in charge of allocation of resources, conflict resolution and in general of medium access control functionalities. This block is in charge of obtaining the PHY-layer performance from the LSLI, generating performance metrics at the radio resource or packet data level and obtaining system level metrics such as throughput, fairness, outage probability, service area, coverage, and geographical information transfer rate (multi-hop settings). This block is also in charge of the self-configuration, multi-hop routing, management of sensor nodes, and also it has an additional functionality of the sensor data management, which in our case is the information of the boundary layer separation between the turbulent and the laminar flows.

An important part of the simulator is the bridge between the wireless network and the internal wireline aeronautical network of the aircraft. This bridge operation requires accurate modelling mainly because the upper layers have different characteristics, requirements, delay deadlines, quality of service requirements that should be addressed by an appropriate proxy server and scheduling technology. The AFDX and the wireless sensor network can be simulated using different instances of the same simulator that communicate with each other via web-services or using a virtual distributed framework for interconnection of simulators, which have been previously proposed in other European projects.

The internal network of the aircraft relays the boundary layer sensed information to ground control which will be in charge of selecting proper actuating policies based on different flight profiles. The selected actuation profile is then communicated to the network of actuators to perform changes intended to reduce the turbulent flow formation.

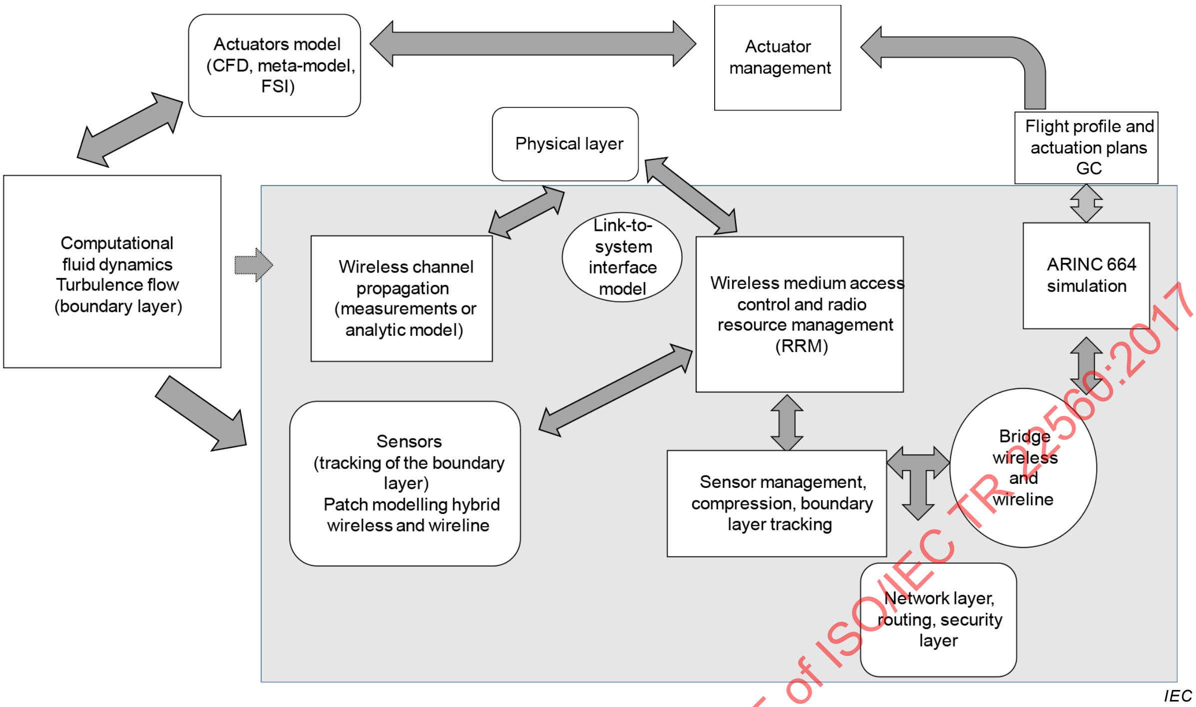


Figure A.1 – Simulator architecture

A.2 Simulation metrics

A.2.1 General

A number of metrics will be implemented to evaluate the performance of the design. Two types of metrics will be used: one set for the fluid domain, and the other set of metrics for the wireless domain.

A.2.2 AFC metrics

A.2.2.1 Lift off force

The average lifting force experienced by the section of the wing under analysis for a given angle of attack.

A.2.2.2 Skin drag reduction

The average reduction of drag due to turbulent flow formation

A.2.2.3 Delay of boundary layer separation

The ability to modify the pattern of turbulent flow to a given specification.

A.2.2.4 Fluid speed profile

The profile of velocity experienced by particles of the fluid. This visualization is useful for interpretation of actuation policies and for the analysis of the interaction of actuators and the free stream flow.

A.2.2.5 Latency actuation

The time required for the system to react to sudden changes in the turbulence profile.