# Active Flow Control for Aerospace Operations by means of a Dense Wireless Sensor and Actuator Network

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## Abstract

This paper presents the design of an active flow control (AFC) system for commercial aircraft based on a dense wired/wireless sensor and actuator network. The goal is to track gradients of pressure across the surface of the fuselage of commercial 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 speeds, longer ranges and reduced fuel consumption. The paper describes the architecture of the system in the context of the European research project DEWI (dependable embedded wireless infrastructure) using the concept of the DEWI Bubble. A simulator architecture is also proposed to model each process of the AFC system and the DEWI Bubble. To the best of our knowledge this is the first approach towards the use of wireless sensor technologies in the field of active flow control.

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***Abstract*—This paper presents the design of an active flow control (AFC) system for commercial aircraft based on a dense wired/wireless sensor and actuator network. The goal is to track gradients of pressure across the surface of the fuselage of commercial 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 speeds, longer ranges and reduced fuel consumption. The paper describes the architecture of the system in the context of the European research project DEWI (dependable embedded wireless infrastructure) using the concept of the DEWI Bubble. A simulator architecture is also proposed to model each process of the AFC system and the DEWI Bubble. To the best of our knowledge this is the first approach towards the use of wireless sensor technologies in the field of active flow control.**

## I. INTRODUCTION

Aerodynamic drag is known to be one of the factors contributing more to increased aircraft fuel consumption. In [1], a study shows that for a long haul commercial aircraft a combined reduction of 10% in both skin friction and induced drag may lead to a 15% fuel consumption reduction alone.

Skin friction drag is the main component of aerodynamic drag. 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 surface of an aircraft, where the flow velocity is lower than that of the free air stream. In some circumstances, smooth laminar flow can be disturbed and become turbulent, which largely increases drag force (Fig. 1). In this transition, flow separation occurs due to a reversed flow at the surface, increasing drag. Both BL transition and separation can be controlled to reduce drag. Skin friction can be reduced by keeping the flow in the laminar regime. Preventing flow separation will thus improve lifting and reduce pressure drag.

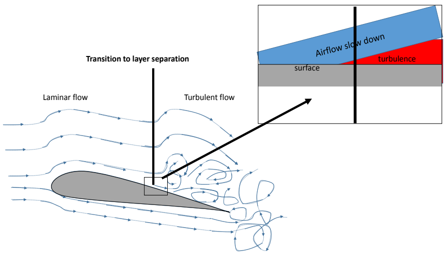

Fig. 1. Boundary layer (BL) transition exemplified with a wing profile.

The position of the BL transition is affected by local flow disturbances, such as: surface roughness, vibration, heat, airstream turbulence, etc. The efficiency of conventional static flow control solutions has been proved low, mainly because resources are wasted when there is no BL separation or when it lies outside the optimal control field. For this reason, active flow control (AFC) approaches have been proposed that enable the dynamic tracking of the BL transition via networks of sensors. AFC has already been targeted by a number of research efforts (e.g., [2],[3],[4]). These works studied different aspects of AFC, including: micro-sensors, actuators, feedback control, and flow instability analysis.

DEWI (dependable embedded wireless infrastructure) is a project that addresses the design of dependable wireless solutions for sensors and actuators in different industrial domains [5]. The core of the DEWI solution is the concept of the DEWI Bubble, which will provide a standardized interface to heterogeneous wireless/wired industrial sensor networks with cross-domain re-usability features, common semantics for interoperability, and flexible application development. The goal is to employ a DEWI Bubble to enable the use of a wireless/wired architecture for the deployment of a dense network of sensors and actuators. This solution will attempt to counteract the formation of turbulent flows across the surface of the fuselage of aeroplanes. This paper is organized as follows. Section II describes the architecture of the DEWI AFC system. Section III presents the architecture of the system level simulator for the AFC system. Section IV present

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preliminary simulation results. Finally, Section V presents the conclusions of the paper.

## II. SYSTEM DESCRIPTION AND ARCHITECTURE

### A. Architecture

The objective of the DEWI AFC is to employ a wireless *sensor-actuator and communication bubble* for suppression of the turbulent flow and delaying the BL transition/separation. The sensor network will detect the low-pressure region on the upper surface of the wings. 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 stored data can be analysed to assess system operation during, for example, different flight profiles or moments of a mission (e.g., take-off, landing, and cruise). Ground systems can interact with the *sensor-actuator and communication bubble* to get the data recorded during the flight and process this information to determine appropriate actuation plans (off-line) and analyse the data of the whole fleet. Fig. 2 depicts the approach to tackle the DEWI AFC system.

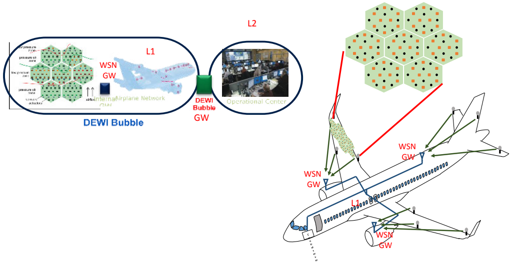

Fig. 2. Architecture of the DEWI AFC.

The AFC system proposed by DEWI consists of an architecture with 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 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 via wireless 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 DEWI Bubble.

The DEWI AFC constitutes a hybrid fusion of wireless and wire-line sensor network components. The information generated by each sensor will be collected by the control unit of each patch (DEWI node) which will provide some preliminary filtering, fusion and aggregation functionalities. The refined information is then relayed towards the control unit (DEWI 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. 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 will be optimized using a simulator described in subsequent sections of this paper. Fig. 3 shows the possible configuration of a regular design of sensor and actuators inside a patch.

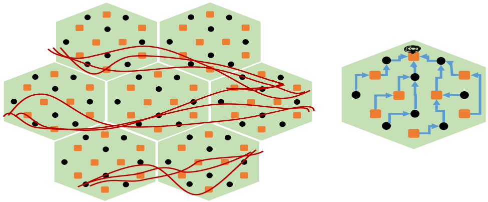

Fig. 3. Array of patches of sensors/actuators.

Another important part of the AFC system is the interconnection of the wireless network into the avionics internal communication systems. The proposed solution has to be able to pass reliably the traffic from/to the wireless sensor/actuator network to the internal avionics network under different quality of service constraints. In general, the AFDX (Avionics Full-Duplex Switched Ethernet) network has more stringent quality of service requirements, therefore the solution must include an appropriate scheduler that will ensure these quality of service constraints of the AFDX traffic are met or conveniently addressed when transported to/from the wireless domain.

### B. Micro-sensors and actuators

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* (see for example [6]). 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 various types of actuators used in flow control applications with different operational principles. Cattafesta and Sheplak in [7] suggested a classification in which the actuators are organized based on their functionality: fluid-based, plasma, mechanical, and others (e.g., electro-dynamic). A common type of actuator is based on flow modification, which uses fluid injection and suction from/to the environment. Two fluid-based approaches are zero-net mass-flux (ZNMF), and non-zero mass-flux. ZNMF solutions are also called synthetic jet actuators (SJAs) [8]. In these actuators the amount of air blown out and sucked in is the same. By contrast, the non-zero mass flux actuators can ingest or expel fluid from/to a source/sink. The DEWI AFC will use SJAs which are designed using a piezo-electric material that vibrates inside and outside a cavity creating a vacuum inwards and outwards, which in turn creates suction/injection of fluid from/to the external stream. SJAs will be designed via computational fluid dynamics (CFD) tools.

### *C. Scalability*

Let us now address a preliminary scalability analysis. Our first assumption is regarding the actuation policy. The simplest possible policy is *on* and *off*. This means that the actuators will be simply switched on when any type of turbulence is detected or switched off if laminar flow is present. Under the worst case scenario, the density of sensing and actuation should be as small as 0.1 mm @ 100 kHz [9]. On the other hand, in the best case scenario, we are looking at sensing density in the order of 1cm @ 1 kHz or even 10 cm @ 100Hz to track the medium spatio-temporal statistics of the BL separation. It can be proved that even a wired technology such as 100 Gbps Ethernet is not able to handle the worst case scenario statistics of turbulent flow to be transported inside the patch. Similarly, a wireless commercial technology (e.g. WiFi or ZigBee) can handle at most values of 1cm@1kHz and 10 cm@100Hz, depending on the number of patches per access point. The conclusions of the analysis is that wireless technologies can handle only certain level of turbulence control, which corresponds to medium spatial-temporal statistics (in the order of 1cm@1kHz and 10 cm@100Hz). This means that the wireless component can be used to control only certain aspects of a flight mission such as changes in direction and angle of attack. Inside the patch, higher order statistics can be addressed using a wired technology. The DEWI AFC system will also employ compression tools to reduce the information to be sent through the wireless component. Boundary detection and Fourier series representation have been analysed in this context. It is important to mention that the compression rate is related to the amount of error introduced in the tracking of the BL. A trade-off analysis is being conducted to understand the abilities of wireless and wired design for the transport of all the generated sensor information. A patch size of about 50cm per side seems optimum in terms of the amount of information generated by a network of sensors and actuators spaced a few centimetres from each other.

## III. SIMULATOR ARCHITECTURE

The architecture of a simulator must closely follow the architecture of the system to be simulated. The simulator architecture is shown in Fig. 4. The first block of the simulator is the computational fluids dynamics (CFD) block, which is in charge of the simulation of the turbulence boundary layer separation and the effects of actuators. The CFD block will provide the information for the network of sensors about how the boundary layer separation is formed in space and time. This information will constitute the traffic input for the wireless sensor network and the patch configuration. The interface between the CFD tools and the simulator has been defined as a stochastic model with spatio-temporal correlation features. This model absorbs the formation of a turbulent flow with a simple mathematical function that describes the boundary layer separation in space and time. In the proposed model, spatial and temporal correlation depend on viscosity, fluid speed, angle of attack and wing profile design. The model is similar to the tools used in envelope wireless channel modelling, only this time employed for the description of the BL separation. The physical configuration of an aircraft and the wing section will be achieved by means of a computer aided design tool or CAD.

The electromagnetic propagation channel model defined by the ITU (International Telecommunications Union) for WAICs (wireless avionics intra-communications) in [10] is used here for an accurate evaluation of the wireless sensor network in aeronautical scenarios. 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 control and signal processing operations. The PHY-layer must interact with the simulator mainly via a compression interface 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. The DEWI AFC solution will consider IEEE 802.15.4 and 802.11 physical layers. The simulator will also consider the effects of interference from adjacent networks such as WiFi- based entertainment systems for passengers. This allows us to design networks resilient to potential interference and jamming.

The core of the simulator is the block in charge of allocation of radio resources, conflict resolution and in general of medium access control (MAC) functionalities. This block is in charge of obtaining the PHY-layer performance from the LSLI, generate performance metrics at the radio resource or packet data level and then obtain system level metrics such as throughput, fairness, etc. This block is also in charge of the self-configuration, multi-hop routing, management of sensor nodes, and more importantly it performs sensor data management, which in our case is the information of the BL separation between turbulent and laminar flows.

An important part of the DEWI AFC 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 of the upper layers have different characteristics, requirements, delay deadlines, quality of service requirements that must 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 sensed BL separation 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 or delay the BL separation boundary.

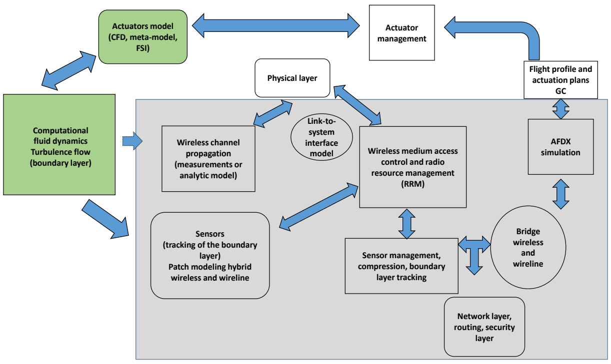

Fig. 4. Simulator architecture.

## IV. RESULTS

This section provides preliminary results of the simulation work performed for the AFC system. The simulation parameters of this tool can be found in Table I. The results of CFD simulation have to be imported off-line into the wireless simulator using a statistical modelling approach similar to the tools used in wireless channel modelling. Fig. 5 shows the results of boundary layer formation using an angle of attack of 24 degrees. The figure shows in circles the instances (random) of the point where turbulent flow starts to form (separation layer). The turbulent model used the statistics of the CFD using an infinite series expansion of chi-square distributions. Fig. 5 shows the profile of a wing, while Fig. 6 presents the view from above the wing, using straight lines to denote the boundary layer formed randomly. Notice we have used three instances of boundary layer formation (three lines). This line is the main element that will be tracked with the objective to counteract the effects of turbulence via actuators. The information generated by each patch is assumed to be transmitted via wireless using the PHY and and MAC definitions of IEEE 802.15.4. The developed simulation tool allows to include several interfering wireless networks reflecting the future of these systems in the avionics industry.

## V. CONCLUSIONS

This paper has presented the design of an AFC system based on a dense wireless sensor and actuator network using the concept of the DEWI Bubble. The paper presented the architecture of the system, the description of the modules and elements that are critical for the operation of tracking turbulent formation across the surface of the fuselage of aircraft. The paper also described a simulator that is being used to design different aspects of the systems including scalability analysis. Simulation results provide useful information about the interactions between the fluid physical world and the wireless sensor domain.

TABLE I
SYSTEM MODELING ASSUMPTIONS.

| Parameter | Value |
|---|---|
| Frequency | 2.4 GHz |
| Bandwidth | 5 MHz |
| Thermal noise | -174dBm/Hz |
| Propagation model | WAICS ITU model |
| Frame length | 15 ms contention mode |
| PHY layer | IEEE 802.15.4 |
| Tx. power | 20 dBm |
| LSLI model | instantaneous SINR mapping |
| Channel model | WINNER B1 |
| Antenna radiation patters | omni-directional |
| Scheduler | round robin |
| CFD interface | Spatial-temporal correlation model |
| Patch size | 10-100 nodes |
| No. patches | 1-10 |

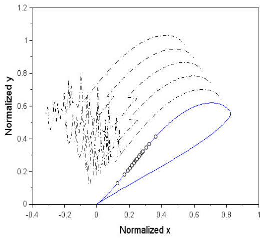

Fig. 5. Wing profile view.

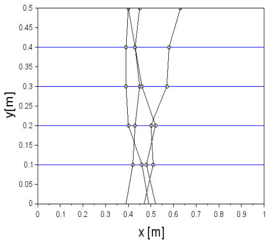

Fig. 6. View from above the wing.

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