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Technical Report

Networked Embedded Systems for Active Flow Control in Aircraft

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Abstract

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Networked Embedded Systems for Active Flow Control in Aircraft

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***Abstract*— Aerodynamic drag is known to be one of the factors contributing more to increased aircraft fuel consumption. The primary source of skin friction drag during flight is the boundary layer separation. This is the layer of air moving smoothly in the immediate vicinity of the aircraft. In this paper we discuss a cyber-physical system approach able of performing an efficient suppression of the turbulent flow by using a dense sensing deployment to detect the low pressure region and a similarly dense deployment of actuators to manage the turbulent flow. With this concept, only the actuators in the vicinity of a separation layer are activated, minimizing power consumption and also the induced drag.**

Keywords-sensor/actuator networks; cyber-physical systems; active flow control; avionics

I. INTRODUCTION

Over the 2009-2028 period, world passenger traffic is expected to increase by 4.7% per annum, and the numbers of frequencies offered on passenger routes will more than double (according to the Airbus 2009-2028 Global Market Forecast). Hence, traffic demand will nearly triple, and airlines will more than double their fleets of passenger aircraft (with over 100 seats) from 14,016 at the beginning of 2009 to 28,111 in 2028 [1].

Although a commercial opportunity, the drastic increase of demand on air transportation presents significant challenges in terms of flight capacity, safety, security, and affordability, as well as, time efficiency and environmental effects. Importantly, the environmental impact of the ever increasing number of flights needs to be reduced. This can be achieved through concepts of aircraft morphing and improved aerodynamics.

The reduction of fuel consumption is important for both the environmental effects as well as the cost efficiency. The potential for a 50% reduction in fuel burn in the next 15 years can be attained using a combination of aerodynamic, engine, and structural improvements [3], as expressed by the well-known Breguet range equation:

$$range = \frac{velocity}{fuel\ consumption} \times \left(\frac{lift}{drag}\right) \ln\left(1 + \frac{weight_{fuel}}{weight_{payload} + weight_{empty}}\right) \quad (1)$$

By inspecting Eq. (1) it becomes obvious that technologies to reduce the aircraft drag and the weight of the empty aircraft are crucial, regardless of selected configuration. Aerodynamic drag is known to be one of the factors contributing more to increased aircraft fuel consumption. In [4], a reported study shows that for a long haul commercial aircraft (325 passengers) a combined reduction of 10% in both skin friction and induced drag (the components that roughly contribute around 80% to the total aerodynamic drag in such type of aircrafts) may lead to a 15% fuel consumption reduction alone.

The drag breakdown of a commercial aircraft shows that the skin friction drag and the lift-induced drag constitute the two main sources of drag, approximately one half and one third of the total drag for a typical long range aircraft at cruise conditions [4, 5] (see Figure 1).

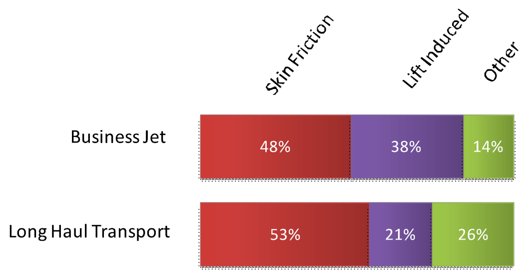

Figure 1. Drag breakdown in commercial aircraft.

Skin friction drag is therefore the main component of the aerodynamic drag. It arises from the friction of air against the skin of the aircraft moving through it. The primary source of skin friction drag during the flight is the boundary layer separation. This is the layer of air moving smoothly in the immediate vicinity of the aircraft (wing, fuselage, tail). The smooth flow (laminar flow) is disturbed by the boundary layer separating from the surface creating a low pressure region and, ultimately, increasing the skin friction drag (turbulent flow). Figure 2 illustrates this.

There are various approaches to reduce the 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) postponing the boundary layer separation using vortex generators such as dimples or Synthetic Jet Actuators - SJAs. In this latter case, suction from the surface of the wing can be used to remove the low-energy air directly from the boundary layer. Along with this method, additional momentum can be achieved by generating streamwise vortices near the edge of the boundary layer that reenergize the boundary layer flow.

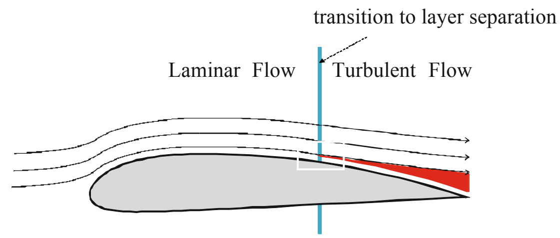

Figure 2. Boundary layer separation exemplified with the wing.

A recent research work [6] uses SJAs running at key positions on the wing to continuously energize the boundary layer and thus delay its separation. However, that approach does not use sensors to detect and trace the separation, and is therefore static and proactive in nature. It results that the efficiency of active flow control (ACF) is compromised and energy resources are wasted when there is no boundary layer separation or when it lies outside the actuators' optimal control field.

We aim a smarter use of the actuators for AFC.

II. A CPS Approach for Active Flow Control

Although the information technology transformation of the 20th century appeared revolutionary, a bigger change is in progress. The term Cyber-Physical Systems (CPS) has come to describe the research and technological efforts that will ultimately allow the interlinking of the real-world physical objects and the cyberspace efficiently [7-8]. The integration of physical processes and computing is not new. Embedded systems have been in place for a long time and these systems often combine physical processes with computing. The revolution is coming from massively deploying networked embedded computing devices allowing instrumenting the physical world with pervasive networks of sensor-rich embedded computation. As Moore's law continues, the cost of a single embedded computer equipped with sensing, processing and communication capabilities drops toward zero. This makes it economically feasible to densely deploy networks with very large quantities of such nodes.

Accordingly, it is possible to take a very large number of sensor readings from the physical world, compute quantities and take decisions out of them. Very dense networks offer a better resolution of the physical world and therefore a better capability of detecting the occurrence of an event; this is of paramount importance for a number of applications where high-spatial sensing (and actuation) resolution is of paramount importance.

Our aimed approach to active flow control is indeed a CPS application where high-spatial resolution sensing and actuation is required, and this opportunity is already being tackled by us [9].

We aim at designing, validating and demonstrating a novel cyber-physical system able of performing an efficient suppression of the turbulent flow by using a dense sensing deployment to detect the low pressure region and a similarly dense deployment of actuators to manage the turbulent flow. With this concept, only the actuators in the vicinity of the separation layer are activated, minimizing power consumption and also the induced drag.

In our approach for turbulence (drag) reduction, we are considering two different types of local actuation (see Figure 3): (i) active vortex generators such as synthetic jet actuators; and (ii) active surface modulation/micro-morphing such as active dimples, active riblets or active fliperons [10]. Concerning the latter, by active it is meant that the local or array geometry is actively changed by a servo-control. These are two different modes of actuation at local level for turbulence management. As far as our knowledge is concerned, none of the technological solutions are commercially (COTS) available yet. In both types of actuation the global concept is the same: a dense network of sensors and actuators will be used to locally modulate the surface and the boundary layer. This dense network aims at maximising sensor observability and improving system controllability.

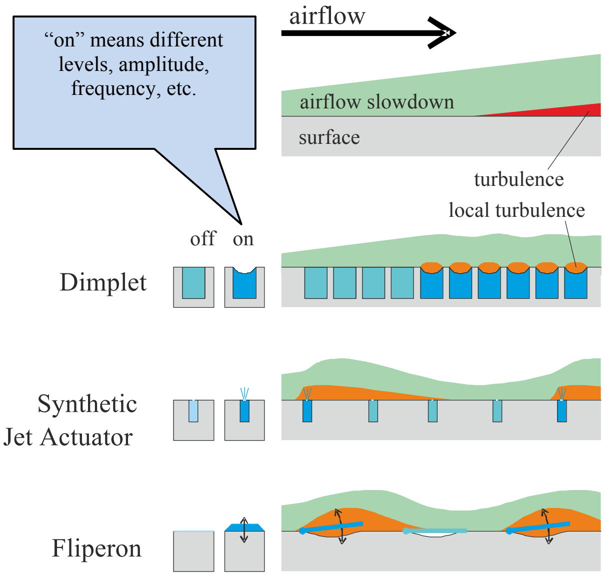

Figure 3. Turbulence management through different local actuation concepts.

The approach we propose for active flow control is challenging however as turbulence management is difficult to achieve. The small length and the time scales that characterize turbulent flows make the design and fabrication of arrays of sensors and actuators very challenging [11]. Active flow control, achieved through local modulation of aircraft skin surfaces, is one such, yet to be seen, technological development with the potential to offer significant reduction of drag and related fuel consumption and emissions.

We want to rectify this.

The challenge is to achieve the desired objective in a dependable manner whilst minimising energy expenditure.

Implementing active flow control through this smart skin approach implies a reliable, highly fault tolerant network of active skin friction reduction components. Importantly, given the characteristics of the physical quantities to be tracked, sensors (e.g., pressure sensors, vibration sensors) might need to be only a few centimetres apart. Therefore, even in the case of a medium-sized passenger aircraft, the sensor / actuator network will be composed of potentially hundreds of sensors, controllers and actuator systems (smart skin patches) (Figure 4) that will be embedded across the aircraft wings and fuselage. Overall, this will be thousands of sensing and actuation devices to perform active flow control.

The concept will be materialized as an active skin system. This active skin system will call for novel solutions in the field of advanced materials for critical applications to drive the effort of integrating the sensors and actuator systems patches with light smart materials technologies (e.g., piezoelectric materials, dielectric elastomers) and integration technologies (e.g., flexible materials, optical fibres, micro-electrical-mechanical-systems). An actual prototype is to be developed.

Such densely instrumented active skin poses a huge challenge in terms of interconnectivity and timely data processing. We plan to develop novel sensor/actuator network paradigms and mechanisms able to deal efficiently with large-scale processing requirements. Scalability will be a concern as well as timeliness. We have already proposed algorithms for obtaining an interpolation of sensor readings from different sensor nodes, and those algorithms present excellent scalability properties for dense instrumented CPS [9, 12]. The active flow control algorithms must operate in a timely fashion to be able to perform efficient flow turbulence cancelling and therefore contribute to a highly efficient fuel consumption reduction.

In our approach, the energy-efficiency of the system is a major concern. Wireless communications [9, 13] are being considered in our concept. In such way we plan to remove the need for complex, heavy (as it is obvious from Eq. (1), cables would increase the aircraft empty weight and therefore would reduce the aircraft range for the same fuel), fixed and replicated wiring looms normally required to implement double or triple redundancy. This is actually in line with the huge eagerness by the industry towards fly-by-wireless [14-16]. However, wireless communication within an aircraft requires advanced security and reliability features. These aspects are being considered in our concept. However, cryptography or error correction schemes have a non-negligible impact on the energy consumption of autonomous sensor nodes deployed within the aircraft. Integrating energy-efficient support through reconfigurable hardware acceleration for these functionalities will be considered to enhance the dependability of the system.

Our recent research [17] has shown that those technologies are achievable for sensor / actuator platforms to be embedded with aircraft structures for even very demanding applications, such as vibration detection and noise cancellation.

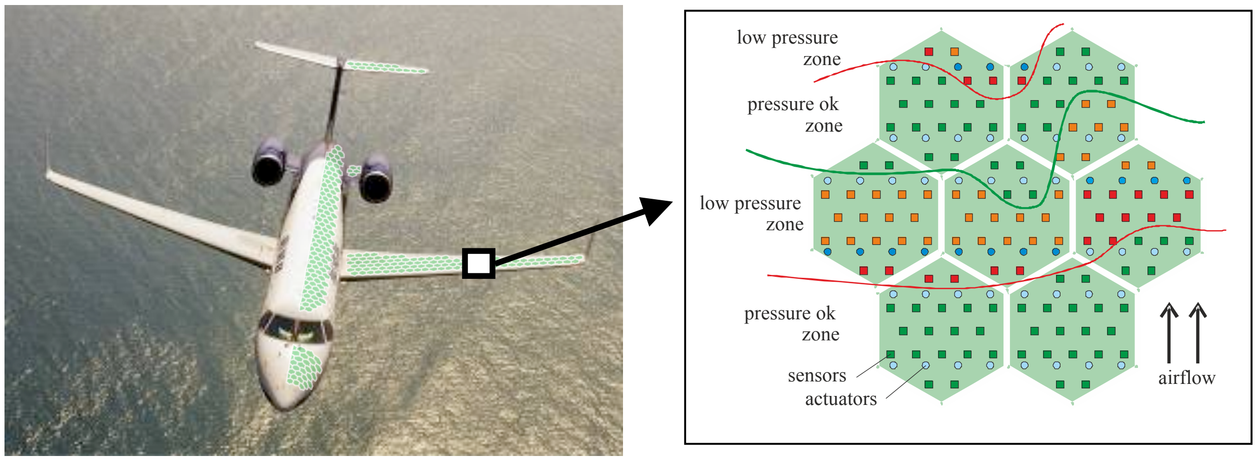

Figure 4. The active skin patch concept.

In this case, an application-specific processor is introduced and fully customized to improve the computational performance of each operation in the digital signal processing algorithms. A similar approach is followed in the project Maintenance on Demand (MoDe) [20] for condition-based maintenance of selected parts of a truck, or in the research project AdRIA (Adaptronics, Research and Innovation) for adaptronic applications [18]. Existing solutions include the utilization of low power reconfigurable computing [21] or specialized streaming processors [18].

Given the high density of sensors and actuators to be deployed for active airflow control, the aggregate power consumption requirements are expected to be relatively significant. This can potentially impact the fuel economy in case some or all of this power is supplied by the aircraft. Therefore, in our concept we plan to explore battery powered solutions and energy harvesting techniques that will exploit structural vibration to generate electrical energy. Some nodes like actuators, which have higher power requirements for actuation, processing, and communication, will possibly operate on the aircraft power supply. Some sensors may also be powered by the aircraft to provide added design redundancy and enhance the overall network reliability. In any case, maximizing the energy efficiency of the active skin is an important design goal. Skills exist as well to explore and propose solutions where sensor nodes can drain power from a layered substrate (such as the Pushpin concept of MIT [19]).

With our approach, the sensing capabilities of the active skin system are also to cover as well Structural Health Management (SHM) functions. Besides pressure sensing capabilities, other sensors may be integrated in the system to convey structural-health information. In that way, real-time information from the aircraft skin (both concerning aerodynamics and structural-health) can be made available to the avionics systems for pre-flight checks and during in-flight operation. This key information can potentially be invaluable for optimising fuel, operational readiness assessment and structural health management planning policies to achieve even other levels of efficiency [22].

We aim at considering dependability as a crosscutting aspect of the system. It is felt this is fundamentally important to the concept and gives it a unique contribution and direction. The reason behind this is not related to the intention of delivering a certified system, but instead it is aimed to direct the other areas of research so that methods and techniques are not developed that are un-certifiable. A particular example is that whilst we could develop a dependable communications infrastructure, however unless we can gather evidence of dependability then it is not useful. This is a particular concern for instance as many communications protocols use highly adaptive features that are normally not allowed by certification standards, e.g. DO178B [23, 24].

III. Related Work and Challenges

A. *Aeronautical applications of WSANs*

Some of the many potential benefits of using Wireless Sensor/Actuator Networks (WSAN) for aircraft systems include weight reduction, ease of maintenance and an increased monitoring capability. Current systems, which are based on wired connections, are complex, difficult to route, heavy and prone to damage and degradation due to wear. The idea of using WSAN in aircrafts so far has been primarily focused on structural and engine health monitoring. For example, Harman [2] summarizes some applicable wireless technologies and [25] describes the architecture of a WSAN for aircraft engine health monitoring, which comprises a number of sensors and a central engine control unit. Interestingly, operational WSAN in spacecraft applications can be found in the International Space Station and NASA's Space Shuttle. WSAN have been successfully deployed to gather data in retrofit applications, which otherwise would have been prohibitively difficult or expensive [26]. In terms of health monitoring for aeronautic applications, special care must be put in the robustness and the security of the data collection process [27].

In the context of aircraft with morphing capabilities, monitoring the shape of morphing structures has been deemed essential for their effective and safe operation [28]. In that work, a novel class of sensors was introduced to address the limitations with previous attempts to monitor the shape and health of morphing structures using fibber optic sensors. It relies on a specially configured distributed network of wires that is embedded in the composite fabric of the monitored structures. The output of the sensor network is wirelessly transmitted to a control processor to compute the linear and angular deflections, the shape, and strain maps over the entire surface of the morphing structure.

B. Communication in large-scale Dense WSANs

In our initiative we are interested in building a distributed sensor/actuator control system, where the sensing and actuating is performed at a very fine granularity in space and time. To achieve this goal, it is necessary to observe that there is a close interaction between the computation (performed by the control algorithms) and the physical quantities (e.g. air pressure, vibration). The control algorithms should perform computations that are based on sensor readings from many sensor nodes, in order to acquire a high-resolution representation of the state of the physical world. To this end, sensor nodes must communicate using a shared broadcast medium (such as a shared bus or a wireless channel), as it would be unfeasible (due to the number of nodes) to deploy dedicated communication channels for each sensor/actuator node. Finally, we would like to be able to acquire this representation with a low (and bounded) delay. This follows from the fact that the control algorithm should do its computations based on a representation of the state of the physical world that is not too old.

Due to the large number of devices, wireless communication bemomes challenging, and obtaining a representation of the physical world with a low (and bounded) delay can be a major obstacle. To overcome this obstacle, it is required to enable energy-efficient in-network processing targeting minimization of wireless communication, thus reducing the probability of network congestion, critical packet losses, transmission delays, as well as improving network lifetime (due to lower energy consumption).

Many research efforts have focussed towards optimizing the process of collecting data from wireless sensor networks. It is possible to find, for example, approaches to minimize the energy consumption in radio-usage [29], or to make use of spatial correlation of sensed data [30] to reduce the number of message exchanges. Efficient data collection can also require in-network aggregation schemes for reducing the number of packets and also the overall latency. Aggregation in wireless sensor networks is a well-researched area with several well-known techniques [31-34].

Collecting data from high-density networks can make use of specific properties of the communication medium to collect aggregates in fast and energy-efficient manner. WiDom [35] is such a medium access protocol that can be employed to efficiently compute aggregates in a timely manner with significantly lesser message exchanges, as shown elsewhere [35, 9]. With that approach, the number of messages exchanged and time to gather an aggregate are not dependent on number of nodes in a given broadcast domain, thus facilitating dense networks without correspondingly high-energy costs.

As mentioned earlier, gathering data from dense networks can also cause latency issues that may not be favourable for real-time control applications. In [36] are outlined various challenges in real-time communication in sensor networks. Quality-of-Service oriented approaches, like [37], provide probabilistic timing and reliability guarantees based on the application requirements. Such provisions are necessary in systems with real-time requirements, and especially in critical systems employed in aeronautical applications. Reducing the radio power can help not only to achieve energy-savings, but can also limit the radio-coverage in dense networks, thereby reducing packet collisions. Low-power radio designs [36, 37] have been proposed that can help on achieving the above goals.

Another approach to reduce the delay induced by wireless communication is the adoption of decentralized computation. The analysis of sensor data within a small cluster of nodes or locally on single nodes with the objective of extracting data features relevant for the application will contribute to the reduction of the communication traffic. However, it must be ensured that the energy and time saved on the communication is not lost with the additional processing. The computation capabilities of the node must be then adapted accordingly, using for example reconfigurable computing [21].

C. Control in Large-Scale WSANs

The design of the control system and actuation are an important aspect that requires skills in control system design, aerodynamics, and system simulation. Consider many sensors and many actuators that are attached to a surface. We desire to control the surface to achieve a certain objective, for example, if the surface is an aircraft wing then we may desire to minimize fuel consumption. The research literature in feedback control systems refers to such a system as a MIMO-system. It is possible to design a single controller for such a system but typically the problem is decomposed into many SISO-controllers, which exchange information. In [38] the authors address the issue of control algorithms in sensor networks, as traditional control theory is not sufficient for modelling distributed sense-actuate systems.

For the control of turbulent waves with dynamic actuators like SJAs, the goal is to excite a counteracting wave that cancels the disturbances travelling along the surface. A possible implementation is based on feed-forward control concepts, which utilize a reference of the disturbance measured with a suitable sensor and generate the control signal from this. By the application of adaptive filters and the use of an error sensor positioned downstream to the actuator for this task, the on-line optimization of the control signal with respect to the current disturbance signals is enabled [39].

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