On the Use of Reconfigurable Hardware in Sensor System Integration for Airliner Cabin Environment Research

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Abstract
Ever been sick after a trip to paradise? Thought about the quality of the air you breathe on the airplane? Commercial airplane passengers and crews breathe a mixture of outside and re-circulated air, similar to the air in many homes and offices. But the cabin environment is unique, due to the proximity of the passengers, the need for cabin pressurization, the low humidity, and the potential for exposure to common chemical and biological contaminants, all in an enclosed structure. This paper describes the use of reconfigurable hardware in designing a wireless network sensor system for monitoring the aircraft cabin. This paper also describes the airliner cabin environment, reconfigurable sensor system backbone, challenges, features of the sensor system, and trade-offs for the system to be feasible.

1.0 Introduction

Ever been sick after a trip to paradise? Have you thought about the quality of the air you breathe on the airplane? Commercial airplane passengers and crews breathe a mixture of outside and re-circulated air, similar to the air in many homes and offices. But the cabin environment is unique, due to the proximity of the passengers, the need for cabin pressurization, the low humidity, and the potential for exposure to common chemical and biological contaminants [1-3]. Commercial aircraft operate in widely varied external environments from taxiing, takeoff, cruise, and descent. The outside temperate can vary between -55°C to over 50°C in a matter of minutes. The ambient pressure can range from 10.1 kPa to 101 kPa. At typical cruise altitude of 11,000 m (36,000 ft), the atmospheric pressure is only about one-fifth that at sea level. In addition, the humidity can vary from virtually dry to greater than saturation. In order to transport people in these extreme environments the aircraft are equipped with environmental control systems (ECS) to provide a suitable indoor environment. The ECS is designed to ventilate and pressurize the cabin. It minimizes the concentrations of contaminants in the cabin when contaminant exposures do occur.

Much research has been done to investigate the link between flying in a commercial airliner and health issues. Passenger and flight attendants have reported sickness after flying, however, due to the manner of how the data was collected and interpreted, no conclusive link can be established. This is the reason why Congress directed the Federal Aviation Administration (FAA) to request that the National Research Council (NRC) perform an independent study to assess the contaminants of concern in commercial aircraft, their toxicological and health effect, and provide recommendations for approaches to improving cabin air quality. NRC was twice requested to carry out such a mission. Two reports were produced, the first in 1986 and the second in 2002 [1,4]. From these reports, the Federal Aviation Administration (FAA) was asked to monitor the cabin environment.

This paper describes the use of a Field-Programmable Gate Array (FPGA) in designing a sensor backbone that is scalable and flexible by the Center of Excellence for Airliner Cabin Environment. The sensor backbone is required to be flexible and scalable because the type and number of sensors have yet to be determined. The flexibility and scalability of the backbone will allow any type of sensor to be quickly prototyped to study the cabin environment. This sensor
system will consist of a base station with multiple remote sensor stations to collect data. The base station is responsible for coordinating data collection, data analysis and storage of all data to persistent media. Each remote station will contain an array of $m$ sensors to monitor the cabin air environment. The base unit and remote stations communicate using a 2.4 GHz Frequency Hopping Spread Spectrum (FHSS) wireless protocol [5,6], in addition, all units will be battery powered. This allows the sensors to be easily integrated into existing aircraft without the need to run additional wiring for power and communications. It is foreseeable in the future that this type of sensor system will be placed in future generations of commercial aircraft to monitor and study the cabin environment.

This paper is organized into five sections. Section two introduces FAA Center of Excellence for Airliner Cabin Environment Research. In Section three, an overview of air supply to cabin is presented. Section four describes the wireless sensor network using reconfigurable hardware. Conclusions and future research are then presented in Section five.

### 2.0 Airliner Cabin Environment Research

The FAA established the Center of Excellence for Airliner Cabin Environment Research (ACER, http://acer-coe.org) in 2004 to examine cabin air quality and to study chemical and biological threats in airliners. ACER consists of an eight-institution team, including Auburn University, Purdue University, Harvard University, Boise State University, Kansas State University, Lawrence Berkeley National Laboratory, the University of California Berkeley, and the University of Medicine and Dentistry of New Jersey. This team brings together the diverse expertise necessary to conduct research on all facets of the airliner cabin environment. ACER conducts a comprehensive and integrated program of research and development on the cabin environment. This includes the healthfulness of the cabin environment for passengers and crew, and the enhancement of the aircraft environmental control systems aboard the aircraft. The portion of ACER research being conducted at Boise State University is sensor system integration. Reconfigurable hardware has been chosen as the central processing unit (base and remote stations) for this project because of the non-deterministic (not knowing the type of sensors to be deployed until completion of the sensor evaluation project) nature of the problem. Reconfigurable hardware is characterized by the property that its low-level logical functionality is not determined at the time of manufacture, but rather that this functionality becomes set only shortly before or during the invocation of the targeted application. This reconfigurable hardware characteristic allows ACER to build a backbone that can be customized as desired.

### 3.0 Aircraft Cabin Environment

At a typical cruise altitude of 11,000 m (36,000 ft), the atmospheric pressure is only about one-fifth that at sea level. The minimal cabin pressure is set by Federal Aviation Regulation (FAR) 25, which requires the pressurization system to "provide a cabin pressure at altitude of not more than 8000 ft (2,440 m)" under normal operating conditions (about 75 kPa). At this pressurization, the partial oxygen level is at 74% of the sea level value. This partial oxygen level does not bother those healthy passengers. However, those with health issues may be at risk.

A number of aircraft systems are involved to maintain the safety and comfort of the environment including propulsion system, which is the source of pressurized air; the pneumatic system, which processes and distributes the pressurized air; and ECS, which conditions the pressurized air and supplies it to the cabin [1]. The ECS pressurizes the system when in flight and controls thermal conditions in the cabin. The ECS also ventilates the cabin with outside air to prevent contaminant buildup and prevent rapid changes in cabin pressure.

Almost all large aircraft (over 100 passengers) manufactured or in service today use ECSs based on bleed air. Figure 1 presents an overview of the bleed air system. Compressed air called bleed air is extracted from the jet engine compressors and supplied to one or more air
conditioning packs. For those with an ozone converter, the compressed air is passed through to purify the ozone. The conditioned air from the packs is supplied to a mixing manifold that distributes it to zones in the cabin. Air movement is predominantly transverse (not front to back). Usually, air is supplied and exhausted along the length of the cabin. Air is supplied through diffusers located in the center of the ceiling aisles, above windows, or along the overhead baggage compartments. Recirculation fans extract air from the cabin at floor level, pass it through filters, and supply it to the mixing manifold. Accurate cabin pressure is maintained by one or more outflow valves. Typically, large commercial aircraft re-circulate about 50% of cabin air passing through high efficiency particulate air (HEPA) filters. It should be noted that there is no regulation requiring the use of HEPA filters. About 85% of the commercial airliners, which carry more than 100 passengers in the US fleet, are equipped with HEPA filters [1].

At cruise altitudes, the outside air generally quite pure and requires no additional cleaning. However, the outside air near ground level could contain a wide variety of contaminants from industrial and urban sources. In addition to the outside air contaminants, the air supply system can be contaminated by leaking hydraulic fluid, spilled fuel, or deicing fluid.

Some of the contaminants found in the aircraft cabin air which may be of great concern are, Ozone, Carbon dioxide, carbon monoxide, Nitrogen dioxide, PM$_{10}$, PM$_{2.5}$, Formaldehyde, Acetic acid, Acetone, Acetylaldehyde, Acrolein, Benzene, Ethanol, Ethylene glycol, Toluene, Xylene, Bacteria, Fungi, and Pyrethrum [1]. Passengers and crews may exposed to these contaminants which could have originated from outside air and organic compounds generated by emissions from materials in the cabin and the human body.
4.0 Wireless Sensor Network for Aircraft Cabin

ACER needs a flexible and scalable wireless sensor network for cabin environment research. This wireless network will have a base station (one for now, may have two to increase network reliability) for centralized data collection and with multiple remote stations where air quality, biological, and chemical sensors will be installed. The base and remote stations will be connected using 2.4 GHz FHSS wireless transceivers. Figure 2 shows a picture of the wireless system. The remote sensor stations are the heart of the system. The primary design criteria of the remote sensor station is their flexibility to accept the widest variety of sensors and their ability to reconfigure on the fly to interface to new sensors as they are added. An FPGA is used as the controller for this unit. The FPGA is responsible for communicating with the wireless transceiver and for controlling the sensor peripheral units. Each remote sensor station will contain 1 to m sensor peripheral units.

Each sensor peripheral unit will contain a microcontroller with one or more sensors interfaced to the microcontroller. Since most sensors are analog in nature, the microcontroller can utilize its integrated A/D capabilities to take sensor measurements. The FPGA and microcontroller communicate using a standard protocol, allowing the FPGA to issue commands to measure data and retrieve the results. By utilizing a separate Sensor Peripheral Board, specific circuitry and microcode for each sensor can be abstracted from the FPGA, allowing maximum flexibility in designing the sensor array. Since the sensors are located on the Peripheral Sensor Board, different Peripheral Sensor Boards with entirely different sensors can be plugged into a remote sensor station, easily changing the parameters and contaminants being measured.

The current design uses a Xilinx FPGA with a Microblaze core as the controller on the remote sensor stations. Our Peripheral Sensor Boards are built around Microchip PIC microcontrollers, although any microcontroller from any manufacturer could be used so long as it implements the I^C protocol.
The remote stations are the backbone electronics that interface to the sensors. The backbone is required to be flexible because different sensors from various vendors will be tested, evaluated and deployed. The backbone is also required to be scalable so that no physical changes need to be made when new sensors are added. This means that the backbone will need to have enough ports for future expansion and the capability to interface to analog or digital sensors seamlessly. The FPGA has been chosen as the solution for a flexible and scalable sensor backbone for this wireless network. However, this only works if the sensor has digital interface. There are sensors with analog interface. The current design involves a PIC microcontroller to interface to analog sensors. In fact, the PIC microcontroller can be used to interface to digital based sensors as well. The PIC microcontroller is also tasked to pre-process the raw data from sensors before being delivered to the Xilinx Microblaze processor core in the FPGA. The Microblaze processor core will package the data packets from all the sensors connected to it before sending to the base station. For the first generation of this network, the sensor data will be delivered to the base station. In the future, this wireless network can be setup so that the sensor data is stored on the remote stations (distributed).

4.1 Base Station

The base station contains a 2.4 GHz wireless transceiver, a secure digital flash memory card for persistent storage and an FPGA to act as a controller for the unit. In the future, it is planned that additional circuitry will be developed that can deliver real time information to the flight crew or possibly even to a ground station for further monitoring. It is also planned in the future that the base station could perform real time data analysis of the incoming data. In the case of a contaminant spike, the base unit could instruct remote units to take additional data to help determine the source and significance of the event. In this case, the FPGA containing a Microblaze core provides us with great flexibility and processing power to perform this data analysis.

4.2 Remote Station

The remote station consists of a FPGA, 2.4 GHz FHSS wireless transceiver, and sensor signal breakout connectors [5]. On top of the FPGA board, a sensor signal breakout board is designed to allow \( m \) number of sensor connectors. A Xilinx Microblaze processor will be the main controller residing in the FPGA to manage up to \( m \) number of sensors. The Microblaze processor can communicate to a sensor if it is digital based. Otherwise, a Sensor Peripheral Board is used. The Microblaze processor communicates to sensor through \( \text{I}^2\text{C} \) protocol. The use of this protocol allows a large number of connections using just two wires!

As shown in Figure 3(b), there is a sensor input/output (I/O) signals breakout board on top of the FPGA board. If more sensors are to be added to the sensor backbone, in the case when there are no more ports on the on the signal breakout board, the sensor breakout board can be modified with little effort.

4.3 Sensor Peripheral Board

The Sensor Peripheral Board (SPB) is where most sensors will be placed and the SPB unit will connect to the base station through \( \text{I}^2\text{C} \) protocol. The role of the SPB is to acquire data from a sensor, carry out conditioning as required, and then delivery the result to the remote station using \( \text{I}^2\text{C} \). Sensors with \( \text{I}^2\text{C} \) interface can be directly connected to the remote station FPGA through the Signal Breakout Board. A low-cost (~$6) Microchip PIC microcontroller is placed in the SPB because different sensors will require different amounts of signal conditioning. Having a microcontroller close to the sensor allows easy interfacing to various types of sensors. In addition to the flexibility provided by the microcontroller, a prototype area about 2”x1” has also been built into the SPB. It is envisioned that this prototype area will be required for voltage level conversion chip.
4.4 Challenges

Due to the general-purpose nature of this wireless network and operating condition, there are many challenges that need to be solved for this network system to be able to interface with different types and number of sensors simultaneously. The first challenge is that different sensors have different type of outputs. Some sensors have analog output and others have digital output. To make matters worse, the sensor’s output signals are usually at different voltage levels (±3.3 V, ±5 V, ±12 V).

A second challenge is data storage. Scientist and analysts want raw data from throughout the flight so that measurements can be correlated to events during the flight. The frequency of data collection has to be adjusted so that there is enough storage for data to be collected throughout the flight.

Third, the remote station must be scalable. The number of sensors a remote station can interface to must be able to scale up to the maximum number that ACER will ever need. The next level of scalability is that the base station will need to be capable of servicing all of the remote stations.

Fourth, the sensor network will require Electromagnetic Compatibility (EMC) certification before it can be deployed for use in the cabin. This is particularly important so that the operation of the sensor network does not compromise the safety of the aircraft, which will defeat the purpose of this project (to monitor the cabin and to increase comfort level of passengers). The other challenge is power consumption of this system. During the prototyping/research phase of this project, the access to aircraft’s wiring won’t be available to transmit the signals and power the sensor network. If any part of the aircraft’s wiring is changed, this will require the aircraft re-certification. Thus wireless network for communication and battery to power these electronics will be required. Not any wireless network protocols can be used in the aircraft cabin; the only one that has been approved for use is 802.11b [8].

5.0 Conclusions and Future Research

This paper described the design of a wireless sensor network using FPGA for airliner cabin environment research. This paper also provides an overview for the air supply systems to
the aircraft cabin. The remote station design has been completed with ad-hoc network capability. At the writing of this paper, the design of base stations is underway. Six different families of sensors (O₃, CO, Ozone, CO₂, Smoke, Humidity) have also been procured to prove the validity of the SPB method in dealing with analog and digital interfaces. Multiple SPB printed-circuit boards have been fabricated and the circuitries are being migrated from prototyping to these units. These exercises are necessary so that there is no prolonged downtime once ACER has determined the types of sensors to be deployed for the cabin environment research. The FPGA has been used for flexibility in changing the control circuitry.

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Although the FAA has sponsored this project, it neither endorses nor rejects the findings of this research. The presentation of this information is in the interest of invoking technical community comment on the results and conclusions of the research.

6.0 Reference


