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Wireless Sensor Networks for Aircraft Cabin Environmental Sensing

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Wireless sensor networks consist of physically distributed autonomous sensor nodes that cooperatively monitor physical or environmental conditions. One of the greatest benefits of wireless sensor networks is that they are capable of generating a more complete view of the sensed environment by acquiring larger quantities of correlated data than independent sensor monitors. The aircraft cabin is a highly dynamic environment which necessitates the use of more advanced sensing systems. It is with the motivation of painting a better picture of the aircraft cabin environment that such a wireless sensor network is being designed and prototyped. This paper discusses the design considerations required for wireless sensor networks in the aircraft cabin environment, as well as an overview of past and present systems developed for use in aircraft cabin environmental sensing. In addition to the sensor network, supporting tools are also discussed to enable analysis of the data collected. The primary goal of this research is to provide sensing tools to enable better characterization of the aircraft cabin environment.

I. Introduction

In recent years, embedded systems technology has advanced to enable the development of new environmental sensing tools. One such technology which has opened many possible improvements in environmental sensing is wireless sensor networks. Wireless sensor networks (WSN) consist of physically distributed autonomous sensor nodes that cooperatively monitor physical or environmental conditions. Recently, environmental sensing systems have been placed in aircraft cabins to enable a better understanding of the baseline characteristics of the environment.[1,2] Additionally, work has been done to develop computer models of the airflow characteristics within the aircraft cabin.[3,4] While this work has provided some information, it does not provide a full view of the environmental conditions within an aircraft cabin, and generated computer models require experimental validation. Previous sensing systems provided only single node measurements. However, the aircraft cabin environment is highly dynamic, and as such, characteristics vary greatly depending on the spatial location of the sensor node. This problem can be directly addressed with a broad WSN deployment within the cabin. In the following sections we discuss the design of a wireless sensor network for the aircraft cabin environment, and more specifically, outline the requirements and design considerations that were applied to the design developed during this research.

II. Aircraft Cabin Environment

The aircraft cabin is a semi-enclosed structure with a mixture of outside and re-circulated air similar to homes and offices. The aircraft cabin differs, however, in that it is a low humidity, low pressure environment with passengers in close proximity. Passengers and crews may be exposed to various concentrations of ozone (O_3), carbon monoxide (CO), carbon dioxide (CO_2), and organic chemicals. The exposure level of contaminants introduced from outside sources depends greatly on the location of the aircraft (e.g. on the ground, in ascent, at cruise, or in decent).[5] With so many variables, it is clear that the aircraft cabin is a very dynamic environment that requires new tools to effectively monitor conditions.

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A. Need for Wireless Sensor Networks in the Aircraft Cabin

In previous research,[1,2] see Fig. 1 and 2, the aircraft cabin environment was characterized by single node measurements. Single node measurements provide a basic understanding of the environment, but there are many factors in the aircraft cabin that can affect the results. In previous non-wireless systems, the sensor node was carried with a passenger and attached to the seat-back pocket to collect data throughout the flight. As the cabin is a semi-enclosed environment, there is a continuous exchange of outside air with cabin air.[5] This results in air flow patterns that are spatially dependent, and as such, the environmental quality measurements can be expected to differ depending on node location. Coordinated measurements in a distributed fashion would enable the characterization of air flow effects and validation of proposed computer models.[3,4] In addition to enabling more accurate estimation of the environment due to the increased area monitored, WSN deployment would enable characteristic measurements that are not possible with single node measurements. One of the possible abilities gained by WSN deployment would be identifying the source of an airborne contaminant as it traverses the cabin. Since the sensor nodes can communicate with each other, a disturbance can be tracked cooperatively by the network.

B. Wireless Concerns

Wireless sensor networks have been proposed for use in structural health monitoring of the aircraft itself.[6-8] In much the same way we propose the use of WSN to characterize the aircraft cabin environment by distributing environmental sensors throughout the cabin. One question raised when considering WSN deployment in the aircraft cabin is whether there could be any adverse interference with flight instruments. Several studies over the years have indicated that the wireless frequencies typically used in WSN systems, such as 2.4GHz ISM band systems, do not interfere with flight systems.[9,10] The broad deployment of Wi-Fi networks within the commercial aircraft is also a strong indicator of the accepted safety of radio transmissions in the 2.4GHz band.

III. Previous Work

In previous work, we developed a standalone sensor node for use within the aircraft cabin. The research was commissioned by the FAA to ascertain the conditions within a typical commercial flight. To meet these goals, we sought to create a low-cost, modular, and reconfigurable design capable of sensing primary environmental conditions such as pressure, temperature, humidity, carbon dioxide, and sound intensity. All collected sensor data was stored on removable secure digital cards.[1,2] Figure 1 shows the external form factor, and Fig. 2 shows an internal view of the module. As seen in Fig. 1 and 2, the initial design provided a reasonably compact package. It was powered by four AA batteries and could collect measurements for 10-15 hours, depending on the set of sensors installed.

The initial hardware met most of the project goals. However, there were several shortcomings. This system did not provide enough isolation of the sensors from the internal hardware which allowed power supply and processor heat to affect

Figure 1. 1st Generation sensor module. *Module dimensions: 15.3 x 9.2 x 5.4 cm.*

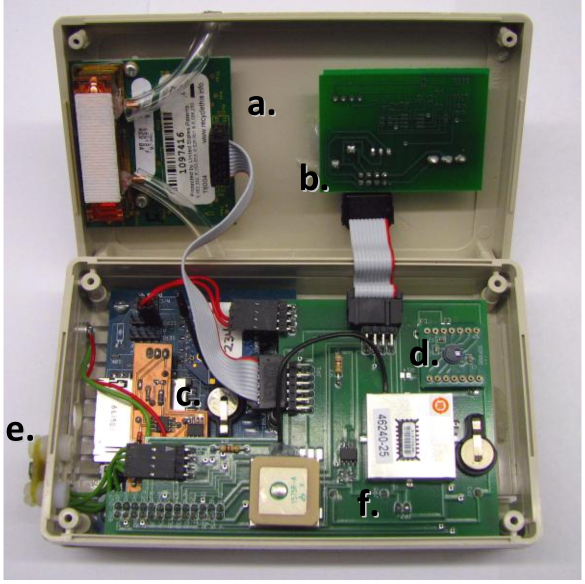

Figure 2. Internal view of sensor module. *a)CO$_2$, b)CO, c)Sound Intensity, d)Pressure, e)Temperature and humidity, f)GPS.*

measurements. Additionally, the internal cabling system proved troublesome over time. Later it was determined that wireless capabilities needed to be improved for general purpose measurement applications.

The hardware platform was then redesigned to incorporate improved modular construction and add networking hardware capable of mesh networking. Figure 3 shows the external design, and Fig. 4 shows the internal layout of the 2nd generation device. This required the design of a custom enclosure and a redesign of the sensor interface boards. The 1st and 2nd generation hardware has captured data on more than 200 commercial flights.[11] The data captured provided a baseline for understanding the current conditions experienced by passengers and crews. To date, wireless network deployment has not been implemented primarily for logistical reasons. With the study being carried out on commercial flights, it was clear that sensor modules could not be left unattended throughout the cabin without potentially alarming passengers (thinking of the reaction of passengers to unusual electronic devices, apparently out of place). Additionally, the internal hardware of the system was not originally intended for large scale wireless deployment, and as such, the processing capabilities of the processor used was not powerful enough to provide measurements with a temporal resolution sufficient for tracking highly dynamic phenomena.

Figure 3. 2nd generation module. *Module dimensions: 16.1 x 13 x 2.7 cm.*

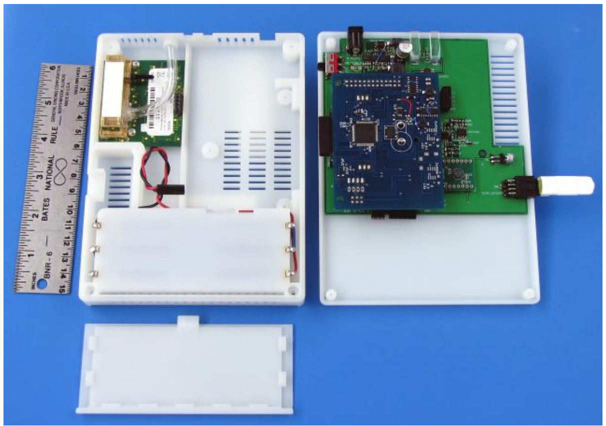

Figure 4. Internal view of 2nd generation module.

IV. Current Work

During this research, there were a number of principles learned with regard to the design of a wireless sensor network system for environmental monitoring. In the following sections we will discuss these principles as well as outline the direction of our current research to develop a WSN backbone capable of capturing highly dynamic events within the aircraft cabin environment. A number of considerations must be taken into account when developing a system of this type. The primary issues are the system components, hardware interfaces to sensors, embedded software architecture, and computer software to interact with and manage the wireless sensor network.

A. Components of a Wireless Sensor Network

Several components will be found on most any wireless sensor system. These include a processor, a power management system, a wireless transceiver, a suite of sensors, and a local data storage medium.

1. Processors for WSN Nodes

The processor must be chosen to optimize power usage, input-output (I/O) capabilities, and power consumption. Typically power consumption and processing power are tradeoffs. However, we have found that this is not always the case. One example of this is directly evident in comparing our original processor selection of a Microchip PIC18F8722 with our current design that utilizes an Atmel AVR32 AT32UC3A3256. The PIC processor has an 8-bit architecture with a maximum operational frequency of 40MHz and a performance of 10 million-instructions-per-second (MIPS) (at 40MHz).[12] The AVR32 has a 32-bit architecture with a maximum operational frequency of 66MHz and a performance of 91 Dhrystone MIPS (DMIPS) (at 66MHz).[13] It should be noted that MIPS and DMIPS cannot be directly compared because the processors have different architectures. There are no published DMIPS numbers for the PIC. DMIPS is a cross-platform measure of performance, while MIPS is a processor architecture dependent measure of performance. Despite these differences, the significant performance improvement with the AVR32 processor is readily apparent, especially considering the data throughput per cycle possible with AVR32's

32-bit architecture (four times the data bus width of the PIC's). Under conventional rational one would expect the power consumption to be equally increased for the AVR32, but this is not the case. At 50MHz, the AVR32 requires 32mA at 3.3V (~107mW). In contrast, the PIC requires 29mA at 5V (~145mW) when running at 40MHz. This difference is primarily due to the advances in the silicon technology. However it illustrates how increases in performance do not necessarily come at the cost of power consumption.

We are concerned with I/O capabilities as they directly control what number and type of sensors can be connected to the system. Table 1 shows a comparison of peripheral I/O protocols available on the PIC and AVR32 processors. As seen in Table 1, the AVR32 processor offers equal or better capabilities in all cases with the exception of the ADC which has fewer channels. As with the power to performance, the I/O capabilities were improved in the new design. (Microchip's PIC32 platform was considered, however its power requirements were nearly double[14] the AVR32's).

Table 1. I/O comparison of microcontrollers.

Peripheral	PIC18F8722	AT32UC3A3256
GPIO	70	110
ADC	1 – 16 channel, 10-bit	1 – 8 channel, 10-bit
DAC	n.a.	1 – 2 channel, 16-bit
I^2C	2	2
SPI	2	2
UART	2	4
USB	n.a.	1 – host/slave

2. *Power Management*

The power system of a wireless sensor node is important to the capabilities of a node. The power management system is responsible for managing the limited energy present in the batteries, and producing voltages/currents that meet the processor's and sensors' needs. Environmental sensors typically require 3.3V or 5V. Therefore, the power system should make these supplies available.

3. *Wireless Transceiver*

Perhaps most obviously, a wireless sensor node needs a wireless transceiver to communicate with the WSN. However, various architectures exist for transceivers that determine the ability of the network to efficiently communicate. The primary types are stand-alone radio, system-on-chip (SoC) processor and radio, and integrated transceiver modules (ITM).

Stand-alone radio designs have the advantage that they require a small amount of board space, and direct communication between the processor and the radio is fast. This is especially advantageous for network topologies that require high speed response times to queries. The disadvantage of stand-alone radio chips is that the processor becomes responsible for managing all of the radio communications protocol stack as well as the normal sensing tasks.

SoC and ITM types eliminate the need for the processor to manage the radio communications stack. These types have a small dedicated processor that manages all radio communications and then communicates with the primary processor with a standard communications protocol such as I^2C, SPI, or UART. ITM types often have a SoC for a transceiver. However, they also include the antenna system. ZigBee is often used in WSN as it supports a wide range of ad-hoc network topologies, and it requires far less power than traditional wireless systems such as Wi-Fi.

4. *Sensor Suite*

The set of sensors required is, of course, dependent on the application. As discussed in our previous work, the primary set of sensors deployed in the aircraft cabin on our sensor nodes to date are CO_2, atmospheric pressure, temperature, relative humidity, and sound intensity. Other relevant sensors that are currently in progress or ready for future deployment include: particle count, carbon monoxide (CO), oxygen (O_2), ammonia (NH_3), volatile organic compound (VOC), accelerometer, and gyroscope.

5. *Storage Medium*

While not strictly required, we have found local data storage to be a significant asset to WSN nodes. A number of activities are made possible by incorporating a local storage medium into the design. Perhaps the most important of which is the ability to log network communication and sensor measurements. With all WSN nodes recording traffic in this manner, "replaying" the events at a later time is made possible. Furthermore, a local storage medium enables the recovery of collected data should a WSN node lose its connection with the network.

B. WSN Hardware

Having selected the primary components of the WSN nodes, the next step is implementation of a design that takes best advantage of the available hardware. One way to do this is to insure that the hardware is both modular and reconfigurable. The level of modularization implemented in our hardware evolved over the course of our research. The current design represents the best configuration identified to this point. The primary dividing line used for modularization in the current system is between the processing, communications, power management, storage

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system, and the sensor interfacing system. In this way, the core functionality of the WSN node is independent of any sensors connected to it. Thus, we have a single system board that has all necessary components for the WSN except for the sensors. Sensor interfacing boards can be created that provide any necessary support circuitry for the sensors as well as any sensors that are required for a particular application.

Figure 5 shows the current system board for our WSN sensor nodes, whereas Fig. 6 shows a sensor interface board attached to the system board. The system board provides 3.3V and 5V switching-regulated power supplies which we have found to meet the typical requirements among a wide cross section of sensor types. The input power can range from 6V to 15V. The board utilizes either a microSD or standard SD card for local data storage (one or the other can be attached at board build time). Beyond the components discussed thus far, the board also has a real-time clock that is useful for correlating measurement times across the network. The sensor interface board attaches through a board-to-board connector that supplies all of the necessary communication protocols to interface with sensors or computer systems, as well as the main power busses.

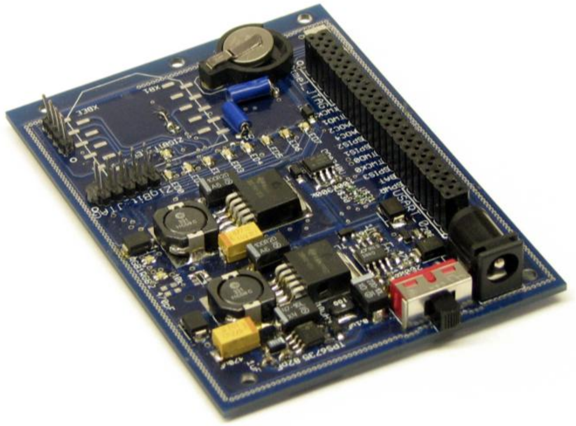

Figure 5. System board for 3rd generation WSN node.

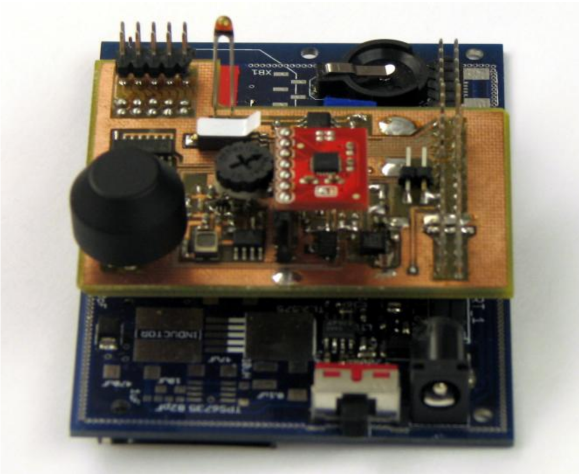

Figure 6. Example sensor interface board. *The sensor board shown provides ultrasonic detector / emitter, accelerometer, gyroscope, magnetometer, temperature, and humidity sensors.*

C. WSN Software

During our research, we found two options for the firmware on the sensor nodes which may provide reasonable performance and reduce engineering time when adding new sensors to the system. The two types are cooperative multi-tasking frameworks and embedded operating systems.

In either case, we have found it important to develop modular, well defined, software architectures to support the various responsibilities of the sensor node. This requires establishing a consistent application programming interface (API) at multiple levels of the software architecture. The abstraction layers are similar to standard computer systems with a few differences. The primary layers include device drivers, sensor controllers, network communications, scheduling, and finally, applications. Figure 7 provides a graphical representation of the architecture.

1. *Device Layer*

The device driver layer provides the interface between the software and low-level hardware of the WSN node. This layer must be as efficient as possible since all interactions outside of the node must be made through the device driver interface. The requirements of this layer differ depending on whether the system is going to run in a cooperative environment or preemptive environment. In the case of a preemptive environment, allowing the device driver layer to block while communicating with the slow devices is generally acceptable. This is due to the fact that the environment can simply preempt the process that is waiting and carry on with other tasks until it is available. In a cooperative environment this is not the case. If a process blocks waiting for a device, the entire system is blocked, and as such, may not be able to meet other deadlines of the system.

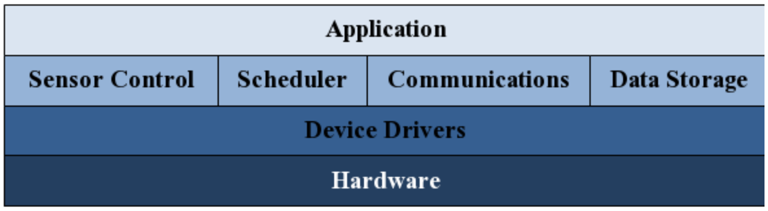

Figure 7. Firmware architecture.

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2. *Sensor Control Layer*

The sensor control layer provides the interface between the application layer and the sensors. This layer relies on the device driver layer to provide the low-level access to the physical sensors. Making this interface common among all sensors is convenient. This can be accomplished by identifying the primary interactions needed between the application layer and the sensors. The basic interactions typically include: *configuration*, *initialization*, *reading*/*writing*, and *releasing*.

3. *Network Communications*

The network communications layer is basically parallel to the sensor and time management modules. Depending on the type of radio system used, this layer may be as complicated as an entire network protocol stack (driver level) or as simple as a basic wrapper for a low-level driver such as SPI or UART that passes messages to an independent radio device (e.g. an ITM).

4. *Scheduler*

The scheduler's responsibility is to manage when events occur on the system. In the case of a cooperative system, this is simply another task that checks a schedule and starts other tasks as their time to run arrives. In the case of an operating system, the scheduler is essentially the kernel process in control of which tasks are to run at any given time.

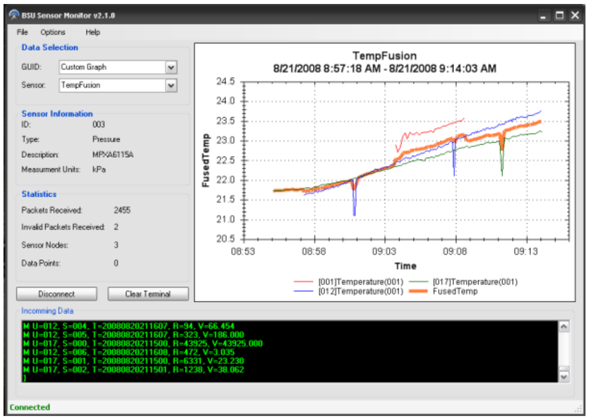
5. *Application*

Finally, the application layer drives the general behavior of the sensor node. The application layer is responsible for initializing the system, connecting to the network, taking measurements, and processing the data. With the other layers properly modularized, the application layer does not need to have access to any of the device specific information and, as such, is portable to other systems.

At the start of this research, the sensor nodes were controlled by a cooperative environment (no formal operating system). However, as the complexity of the system increases, it becomes difficult to maintain optimal performance. Presently, we are in the process of moving to a preemptive, multitasking, embedded operating system to improve performance particularly for sensors that have strict timing requirements such as particle counters.

D. WSN Interfacing Software

Once the sensor network is collecting data, the issue then becomes a question of how to process the data. Depending on the frequency of measurement, the potential of very large quantities of data collected by wireless sensor networks becomes a concern. Many possible ways to interact with sensor networks exist, and this is a very active area of research. Some primary options include storing data locally at each sensor node, streaming all data from each sensor node to one or more "sink" nodes, sending sensor data only when measurement values (or aggregate measurement values) change by some predefined threshold, or only sending data out of the network that is directly requested by an outside party.



GUID: Custom Graph
Sensor: TempFusion

ID: 003
Type: Pressure
Description: MPXA6115A
Measurment Units: kPa

Packets Received: 2455
Invalid Packets Received: 2
Sensor Nodes: 3
Data Points: 0

```
M U=012, S=004, T=20080820211607, R=94, V=66.454
M U=012, S=005, T=20080820211607, R=323, V=186.000
M U=017, S=000, T=20080820211500, R=43925, V=43925.000
M U=012, S=006, T=20080820211608, R=472, V=3.035
M U=017, S=001, T=20080820211500, R=6331, V=23.230
M U=017, S=002, T=20080820211501, R=1238, V=38.062
}
```

Figure 8. BSU Sensor Monitor software.

During the design and implementation of our system, a number of techniques were explored. As a first-order solution, all data was simply stored to removable storage on each sensor node and streamed continuously to a central sink node. Figure 8 shows a screen capture of the prototype software. This system has several drawbacks but also provides a number of advantages (particularly in applications such as the aircraft cabin environment). The primary drawbacks for streaming all data to a single sink node are power requirements and scalability. Neither of these issues is significant in our application of the aircraft cabin environment. The total number of nodes is relatively low, and the total time of operation is less than 18 hours (longest active commercial flight). The benefit of this type of system is a real-time view of the conditions.

With large amounts of data streaming to a sink node, developing a means to effectively view the data stream as well as enable some basic real-time analysis became necessary. This was accomplished with software running on a computer connected to the network via a custom sensor node that relayed network traffic to a computer. The software designed actively logs and plots sensor measurements from all sensor nodes in the network. The current software is configurable to show any set of sensors together to aid in analysis.

In addition to direct viewing of sensor data, the application also has the ability to apply basic aggregation algorithms such as averaging. Figure 9 shows an example of how the software can be used to characterize the environment.

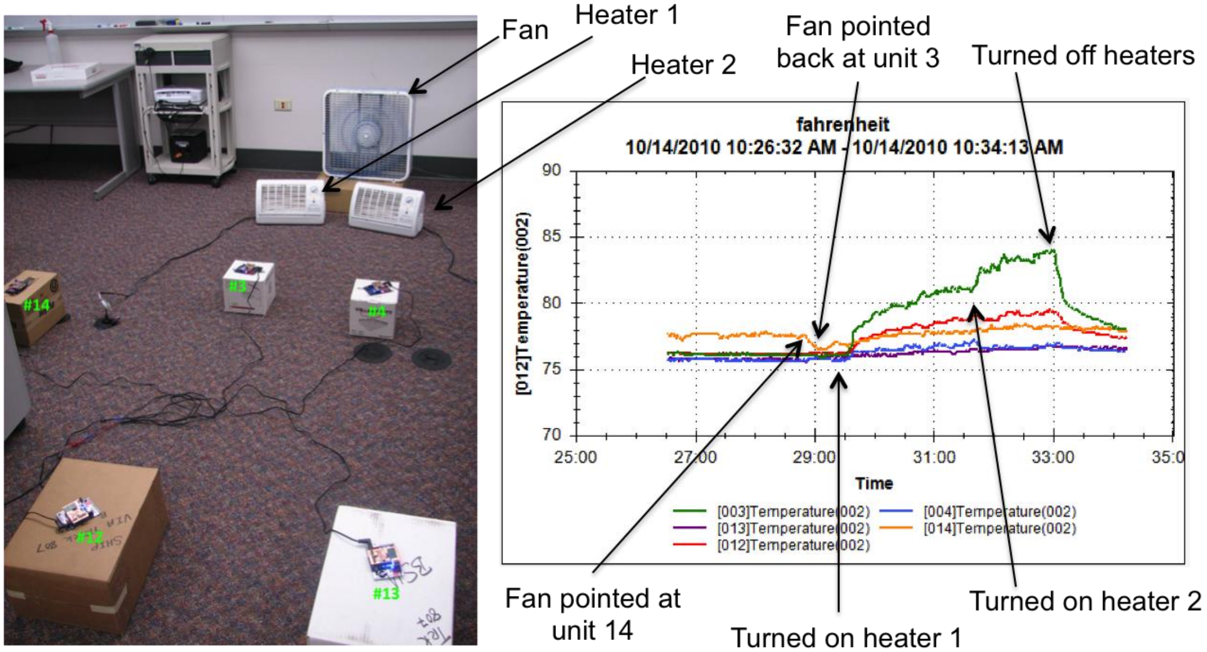


Figure 9. Example test tracking a single environmental variable.

As seen in Fig. 9, a simple test was conducted to detect the changes in temperature as airflow was adjusted in a room. For this test, the sensor nodes were powered with bench-top power supplies (not shown in the picture). The test was as follows. A fan was positioned at one end of the area and left on continuously, creating a constant airflow across the monitored area. Heater 1 was turned on followed by heater 2. After a several minutes, both heaters were turned off. For most of the test, the fan was pointed in the direction of units 3 and 12 as shown in Fig. 9. During the test, the fan was rotated momentarily in the direction of unit 14. At this point, the temperature on unit 14 dropped to match the temperature of the rest of the units. As soon as the fan was pointed back in the direction of units 3 and 12, the temperature began to rise back to its original value. This demonstrates that unit 14 was completely outside the path of the fan, and therefore, its temperature was not affected by the heaters. Unit 3 was the closest to the heater. So, as expected, it detected the largest rise in temperature. The rise in temperature at unit 12 was much less than the value detected at unit 3. This was due to the fact that unit 12 was also in the heat path but farther away from the heat source. From the data, units 4 and 13 detected the least amount of heat. This was due to their position inside the airflow path but outside the influence of the heat source.

The sensor data displayed as a value-versus-time plot is useful for basic analysis. However, other methods can provide a more effective view of the data. To aid in this process, we are currently developing 2D/3D real-time plotting systems that provide contour maps of the monitored area as a function of any desired measurement. This type of analysis system allows for contaminant tracking and origin estimation. The system will be tested using a scale mock-up of a 767 cabin section.

V. Conclusion

In previous research, baseline data has been collected in the aircraft cabin, and computer models have been developed to try to estimate the propagation of contaminants in the aircraft environment. As the environment is highly dynamic, computer models of the environment need to be validated. New tools need to be leveraged to fully characterize the way contaminates move through an aircraft cabin. Wireless sensor networks can provide the necessary coverage and cooperation to effectively monitor this system. A new high-performance wireless data acquisition system is currently under development to meet the particular needs of aircraft environmental monitoring. Many design parameters were considered during the development of the new system, which has proven effective in simulated monitoring of dynamically changing environments.

Acknowledgments

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References

[1] Loo, S. M., Owen, M., Kiepert, J., Planting, A., “Modular, Portable, Reconfigurable, and Wireless Sensing System for the Aircraft Cabin,” Journal of ASTM International, Vol. 4, No. 4, 9 pages, April 2008.

[2] Kiepert, J., Loo, S. M. "A wireless sensor data fusion framework for contaminant detection," Technologies for Homeland Security, 2009. HST '09. IEEE Conference on , vol., no., pp.214-220, 11-12 May 2009.

[3] Zhang, T. and Chen, Q., "Identify contaminant sources in airliner cabins by inverse modeling of CFD with information form a sensor," Proceedings of the 10th International IBPSA Conference (Building Simulation 2007), Beijing, China, 2007.

[4] Mazumdar, S. and Chen, Q., “Response of contaminant detection sensors and sensor systems in a commercial aircraft cabin,” Proceedings of the 10th International IBSPA Conference (Building Simulation 2007), Beijing, China, 2007.

[5] The Airliner Cabin Environment and the Health of Passengers and Crew, Washington, DC, National Academy Press, 2002.

[6] Becker, T., Kluge, M., Schalk, J., Tiplady, K.; Paget, C., Hilleringmann, U., Otterpohl, T., "Autonomous Sensor Nodes for Aircraft Structural Health Monitoring," Sensors Journal, IEEE, vol.9, no.11, pp.1589-1595, Nov. 2009.

[7] Yedavalli, R. K. and Belapurkar, R. K., “Application of wireless sensor networks to aircraft control and health management systems.” Journal of Control Theory and Applications, 2011,9(1):028-033

[8] Demo, J., Steiner, A., Friedersdorf, F., Putic, M., "Development of a wireless miniaturized smart sensor network for aircraft corrosion monitoring," Aerospace Conference, 2010 IEEE, vol., no., pp.1-9, 6-13 March 2010.

[9] Jianhua L., Demirkiran, I., Yang, T., Helfrick, A., "Feasibility study of IEEE 802.15.4 for aerospace wireless sensor networks," Digital Avionics Systems Conference, 2009. DASC '09. IEEE/AIAA 28th, vol., no., pp.1.B.3-1-1.B.3-10, 23-29 Oct. 2009.

[10] Armstrong, N.L. and Antar, Y.M.M., "Investigation of the Electromagnetic Interference Threat Posed by a Wireless Network Inside a Passenger Aircraft," Electromagnetic Compatibility, IEEE Transactions on, vol.50, no.2, pp.277-284, May 2008.

[11] Loo, S. M., Byron, J., “Portable Air Quality Monitor and Wireless Sensor Network for Cabin Monitoring,” The Sixth Triennial International Fire & Cabin Safety Research Conference (Cabin Safety V), 2010.

[12] Microchip, “PIC18F8722 Family Datasheet,” http://ww1.microchip.com/downloads/en/DeviceDoc/39646c.pdf [cited 25 March 2011].

[13] Atmel, “32-bit Microcontroller AT32UC3A3/A4 Datasheet,” http://www.atmel.com/dyn/resources/prod_documents/doc32072.pdf [cited 25 March 2011].

[14] Microchip, “PIC32MX5XX/6XX/7XX Family Data Sheet,” http://ww1.microchip.com/downloads/en/DeviceDoc/61156F.pdf [cited 25 March 2011].