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A LOW-COST WIRELESS PORTABLE PARTICULATE MATTER MONITORING SYSTEM

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SUMMARY

This paper describes a portable sensor system design for environmental research. The designed system has been deployed in many environments and has been EMI/EMC approved for operation in commercial aircraft cabins. The sensor suite includes particulate matter, CO, CO2, temperature, humidity, pressure, light intensity, and sound sensors. Multiple sensor systems can be deployed at once to form a wireless sensor network. Each sensor node is powered either with six AA batteries or via a transformer and standard outlet. The data collected by a node can be stored locally on the device and/or sent through the integrated ZigBee mesh network to a central coordinator node. As of this writing, single nodes have been carried by passengers to monitor the normal airliner cabin flight conditions, and networks have been used to monitor indoor and outdoor air quality conditions.

INTRODUCTION

Wireless sensor network (WSN) research for environmental monitoring has dramatically increased in the last decade. The convergence of improvements in sensor, battery, and semiconductor technology has made the design and deployment of these networks feasible. Sensors designed to measure environmental parameters in real-time such as gas and vapor concentrations, pressure, humidity, and temperature are now readily available in small form factors and at reasonably affordable prices. Yet, a review of scientific literature reveals a gap in the characterization of environmental air quality: a sensor designed to monitor airborne particulate matter in real-time.

While sensors for measuring real-time particulate matter concentrations have been available for decades, most of the commercially available devices have serious drawbacks for incorporation in a WSN. These devices tend to be relatively large, making them cumbersome during personal monitoring applications when they must be worn on a person's body. They are also intended for use as stand-alone units and are generally not appropriate for integration within other compact devices. These factors can make it difficult to include multiple devices into an environmental study and prohibit inclusion of a particulate matter sensor in each wireless sensor node.

The creation of a WSN that includes particulate matter sensors opens many possibilities for new applications that provide benefits spanning areas from health and wellness to material concerns. The investigation of airborne contaminant movement within the highly dynamic environments of aircraft cabins has been facilitated by the use of WSNs. Past studies have deployed WSNs containing suites of gas and other environmental sensors (Kiepert, 2011). The addition of a particulate matter sensor to this suite would provide for the assessment of another important environmental factor determining the air quality of an aircraft cabin. For example, there is significant interest in the measurement of the microbial content of cabin air (Osman, 2008). A particulate matter sensing WSN would aid in the understanding of the movement and concentrations of these and other particulates in the aircraft environment.

This paper describes a portable sensor system design for environmental research. The system has been EMI/EMC approved for operating in commercial aircraft cabins. It has been deployed to airliner cabins, indoor, and outdoor environments. Multiple sensor systems can be deployed together to form a wireless sensor network.

SENSOR SYSTEM

Each sensor node is equipped to measure particulate matter, CO, CO2, temperature, humidity, pressure, light intensity, and sound intensity. The sensor node is powered with six AA batteries or an AC/DC wall adapter. The data collected by each node can be stored to secured digital flash memory (SD card) locally on the device and/or sent through the integrated ZigBee mesh network to a central coordinator node. For a sensor node with a Bluetooth transceiver, the real-time data can be viewed using a tablet, such as the Nexus 7.

Our sensor system incorporates many parts to create an entire solution, including sensor nodes taking environmental measurements, communications infrastructure to relay the measurement information, storage for measurement data, and methods for representing the collected information to the end user. Each of these pieces must work together to achieve the sensor system's mission. At the highest level, the goal is to simplify the collection of high-quality environmental data from a distributed set of points and present it to the user in an understandable form. Figure 1 shows an example deployment of our sensor system.

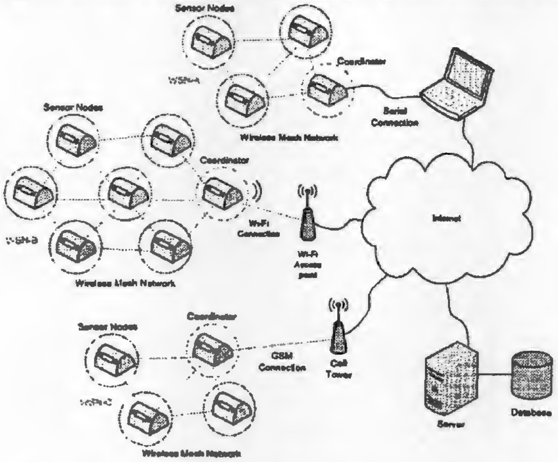

Figure 1. Wireless sensor system diagram.

There are many possible deployments, with multiple wireless mesh networks connected in several different ways to either a database server or an end user's computer. In the example arrangement, three WSNs are attached to the Internet. WSN-A connects to the Internet through a serial connection to a PC, WSN-B through a Wi-Fi access point, and WSN-C through a GSM connection to the cellular network. In the first case, the sensor data from the WSN is passed from the coordinator to the PC which is running software to pass the sensor data on to the database server through the Internet. In the second case, the WSN connects directly to the Internet through its Wi-Fi connection to a local access point and sends its data directly to the database server. Alternatively, the server does not need to be used at all. Data may be passed directly to an end user's PC for viewing with the appropriate visualization software. Data may also be collected only on the end nodes with no transmission and retrieved from each sensor's local storage at a later time to be merged into a single view.

Wireless Sensor Network

Many advantages can be recognized by connecting multiple sensor nodes together with a network. Perhaps of most interest is the ability to provide temporal and spatial aspects to data collection. Linking the multiple nodes can provide more information regarding the environment that cannot be learned with a single sensor. For instance, one might wish to know how quickly particulate matter moves from an indoor source to a room on the other end of the building.

Multiple options exist for building a wireless sensor network (Yick, 2008), including using standards-based implementations or creating a custom network. A standards-based implementation brings many benefits, including behaviours that are typically well defined and tested as well as off-the-shelf hardware and software support. For our WSN implementation, we have chosen to use the ZigBee/IEEE 802.15.4 standards which define a robust, low-power wireless mesh networking solution. Mesh configurations in particular have the benefit of not requiring all nodes to be within communication range of the final destination (coordinator or base) node of the WSN. This can allow very complex and distributed sensor deployment topologies that cover large areas. Several functions built on top of the WSN allow our sensor system to meet some of its critical goals, including flexible data delivery mechanisms and time synchronization.

Within a WSN, the flow of sensor data often moves from the sensor nodes across one or more wireless hops to a single coordinator node acting as a data sink. The Personal Monitor (PMON) sensor nodes implement a network layer on top of the WSN that performs best effort delivery with a relatively small amount of buffering. The buffering is intended to handle limited periods of disruption or congestion. The PMON network layer creates a virtual socket interface between a sensor node and the coordinator. This allows the coordinator to recognize and manage the connections to multiple sensor nodes, and provides a framework for reliable delivery.

For visualization and long-term storage, the data must be delivered from the WSN to a device capable of these functions, typically a personal computer or server. Transferring the data out of the WSN is the responsibility of the coordinator node. For a PMON node (see Figures 2 and 3), multiple options are available for connecting the WSN to the outside world. The PMON coordinator can use USB or a serial port for a wired connection with a PC or server. An 802.11g module may be installed for direct connection to a local wireless access point. If no local Internet connection is available, a GSM data modem can be used to connect into the cell network. When no wired or wireless connection exists or if communication is interrupted, each node may store its data on a local SD card for later retrieval. A key aspect of any WSN is the ability to temporally correlate measurements between nodes. Each measurement must be time stamped in some way to indicate its location in the data chronology. A local time can be maintained at each node through the use of a time-of-day clock, but these will drift over time without synchronization. Many well-tested clock synchronization algorithms are already in existence and can produce very good results (Yick 2008). The PMON sensor system currently synchronizes times by simply pushing the time out to the sensor nodes from a coordinator unit. For relatively small test deployments, this method has typically resulted in synchronization with sub-second accuracy. This algorithm will be modified in the future to provide more accurate and consistent synchronization.

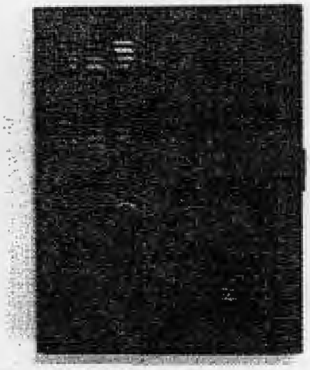

Figure 2. PMON sensor node.

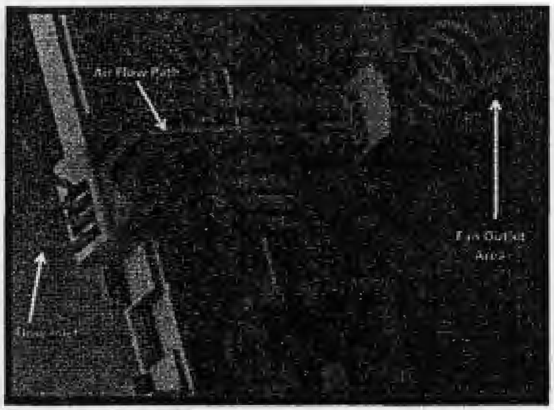

Figure 3. Particle counter airflow and optical path.

Optical Particle Counter

The optical particle counter design operates on the principles of Mie scattering, wherein a single particle intersecting a beam of light scatters photons onto an optical sensor (Baron, 2011). The optical sensor converts the photons into a measurable signal, which is analyzed to determine the particle size. The amount of light received at the sensor will be dependent on the particle size, shape, and index of refraction. Since the shape and index of refraction of each particle may not be known, optical particle counting in uncontrolled environments contains some inherent uncertainty in measuring particle size. The count of particles in each size range is divided by the volume airflow through the measurement area to determine the particle concentration.

Airflow and Optical Path Design

The airflow and optical path are shown in Figure 3. Air enters the sensor from the flow inlet, moves past the laser and photodiode, and exits through the outlet fan area. The fan is not shown in the drawing but would normally fit into the outlet fan area. The laser light passes the photodiode and enters the light trap area where it is absorbed. In order for the particle counter to make accurate measurements, the airflow channel was designed around the sensor in such a way as to allow for a consistent, smooth flow of air. The system segregate particles base on light intensity at detector. The lower detection limit has been shown to be around 300nm.

Particle Counter Calibration

The particle counter is calibrated with Polystyrene Latex (PSL) particles. This material is commonly used in the calibration of optical particle counters (OPC) and is provided as a concentrated particulate of known shape and size in a solution that can be nebulized into an aerosol. The aerosolized PSL particles are injected into a controlled environment containing the PMON units and two commercial OPCs. One of the commercial OPCs is the Particle

Measuring Systems (PMS) Lasair II-110. The second is a TSI 9303 Aerotrak optical particle counter. Figure 4 shows a representative sample of comparison data using ambient indoor air after the calibration process Particle concentrations in blue are from the commercial device, and the data in red is from the PMON particle counter. The upper plot shows concentrations of particles with diameters in the range of 0.3 µm to 2.5 µm, and the lower plot shows particles with diameters greater than 2.5 µm.

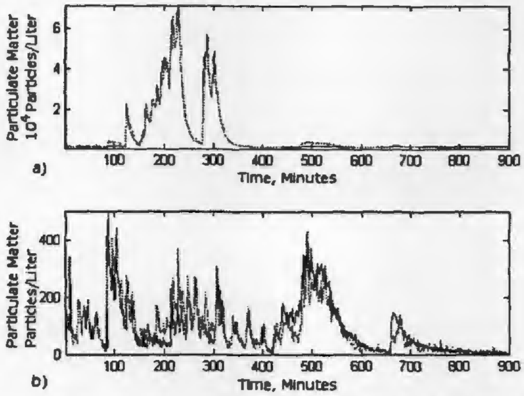

Figure 4. Particle counter comparison with commercial device. Data in blue is from the commercial device and data in red is from the PMON particle counter.

RESULTS

The data presented in this paper has been collected with two systems: desktop and portable systems. These two systems are basically similar in features but different in form factor. The desktop system collected indoor and outdoor air quality conditions in residential settings. The portable system was carried by passengers to monitor the normal airliner cabin flight conditions. A few flights were selected for inclusion in this paper.

Residential

A small set of example data is included here to demonstrate how the particle counter wireless sensor network can be used. Figure 5 shows a set of particulate matter data taken from three different sensor nodes placed within a single-family home. The plot displays particle counts per cubic liter in size ranges from 0.3µm to 2.5µm. Two of the sensor nodes were positioned inside the main house, with one unit in the kitchen and one unit in a study approximately 15 meters away. The third unit was placed in an attached garage, which was separated from the other two units by a closed door.

As noted on the plot at approximately 16:00 UTC, a meal was prepared in the kitchen. This activity generated a large spike in particulate matter that could be seen moving into the study several minutes later as the particulate dispersed throughout the house. Once the particulate generation ended, the concentrations eventually equalized. At approximately 23:00 UTC, a window in the study was opened, allowing air exchange with the outdoor environment. The particulate in the study was reduced during this time period, but the overall particulate in the household was not significantly impacted. The third sensor in the attached garage clearly measured a concentration of particulate that was unrelated to the concentration observed in the home. During the described period there was no forced air circulation in the home. This data demonstrates the sensor system's ability to track the movement of particulate matter through an enclosed space. Though only a small number of nodes were available for this experiment, increasing the node density in the home would give better indication of particulate motion.

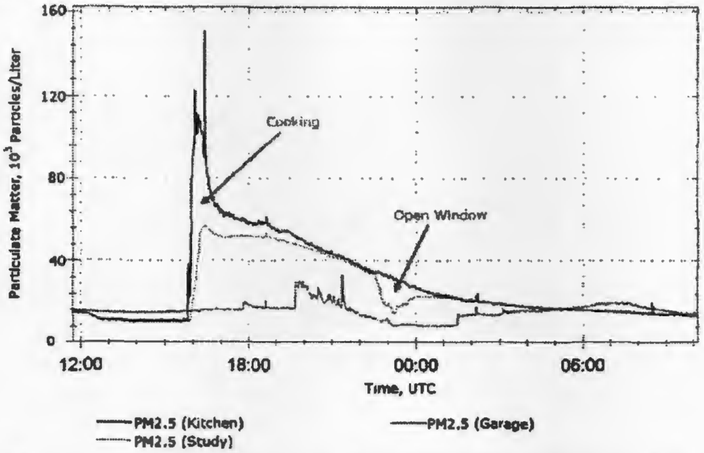

Figure 5. Small particulate measurement from multiple sensor nodes placed in family home.

The data plotted in Figure 6 is taken from a single sensor node, but shows data from multiple sensors concurrently. Notable events include the garage door opening and closing, and the starting of an automobile in the garage. The first time the garage opens introduces a spike in particulate matter, which remains unstable for several hours until the garage door closes. The automobile starting significantly impacts the CO levels in the garage. This time also corresponds with the garage door closing. The temperature, which exhibited quite a bit of instability when the door was opened, stabilized once the door closed. With the door closed, the residual CO from the automobile starting was trapped within the garage. The first indicated point where the garage door opens coincides with the return of the automobile. At this point the trapped CO in the garage escapes, and the automobile's residual heat increases the temperature in the garage. While limited to a single set of events, this data shows how sensor data may be fused to detect events that impact the local air quality.

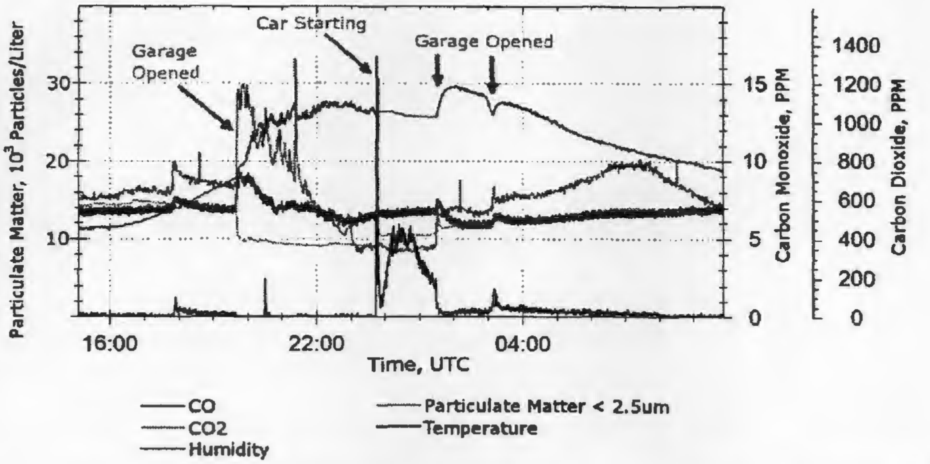

Figure 6. Multiple sensor measurements from a single sensor node. Data taken from the attached garage of a single-family home.

Aircraft Cabin

A set of airliner cabin data is included in Figures 7 and 8 to demonstrate how the system has been used. This data was taken on a short to medium range twinjet narrow-body airliner with business and economy class. The flight was from an airport in the southeast part of the USA to another airport in the southwest part of the USA. Recently, the Federal Aviation Administration has taken steps to allow expanded use of portable electronic devices by airplane passengers. Since our monitor has gone through proper EMI/EMC certification to show that it poses no risk to aircraft flight electronics, we were allowed to operate the monitor gate-to-gate. The monitor is usually hung on the seat pocket.

Figure 7 shows the temperature, humidity, pressure, and CO2 data from this flight. The monitor was turned on as soon as possible when this passenger got to their seat. The cabin temperature trends upward until a passenger complained to an attendant and an adjustment was made. The researcher who carried this monitor indicated that it was very warm throughout most of the flight until the flight attendant adjusted the cabin temperature. This flight took off from a location with high humidity and ended in a location with lower humidity. The data shows the high starting humidity, a decrease caused by the conditioned air within the cabin, and the lower humidity at the destination gate. The pressure data can be used to verify whether the data collected is valid – in the sense that the aircraft went through all the phases of a typical flight – take-off, ascent, cruising, decent, and landing. One can easily infer these phases from the pressure data. The CO2 data indicates a level of 2500ppm of CO2 during the boarding process. As the flight took off, the CO2 level stayed at around 1500ppm. Previous data has shown this to be a typical concentration in the economy class.

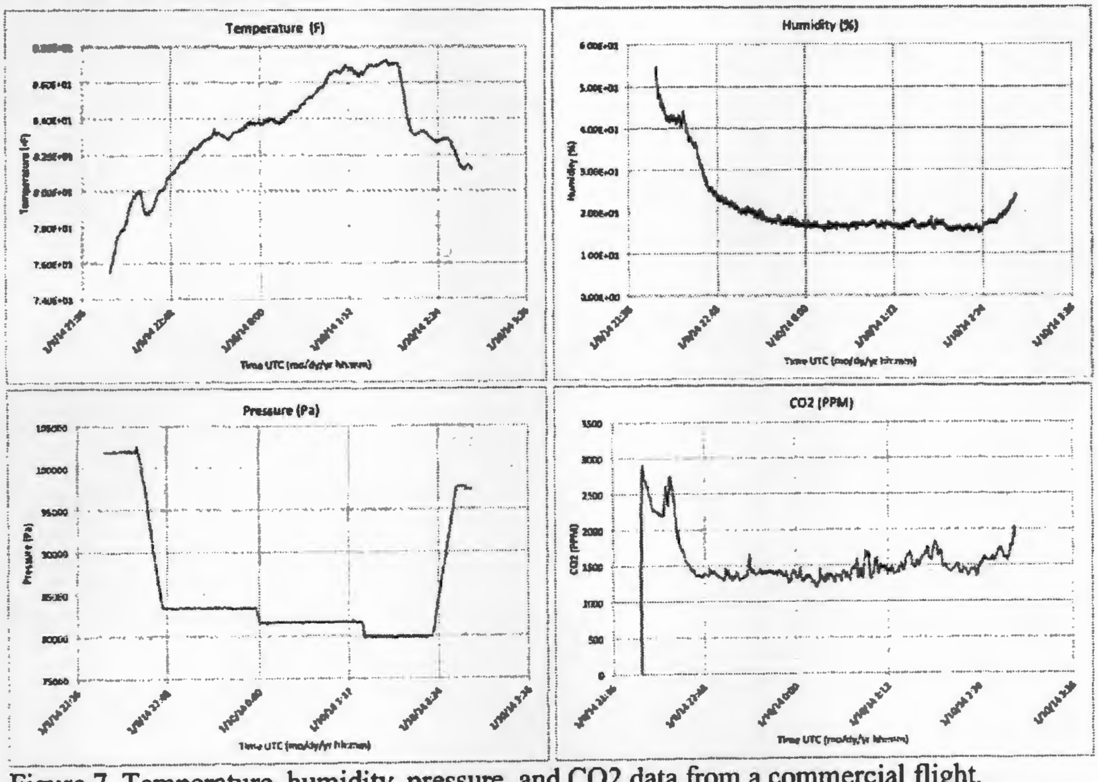

Figure 7. Temperature, humidity, pressure, and CO2 data from a commercial flight.

The particle data is shown in Figure 8. Since we do not have a standard (such as Particle Measuring Systems Lasair II-110) for comparison, we can only do a subjective comparison with the data shown in Figures 5 and 6. In general, the aircraft cabin is a very clean environment. The first peak is a perturbation which is seen whenever the system is first switched on. According to the passenger, the peak in the middle of the flight occurred when they disturbed the device on the way to lavatory.

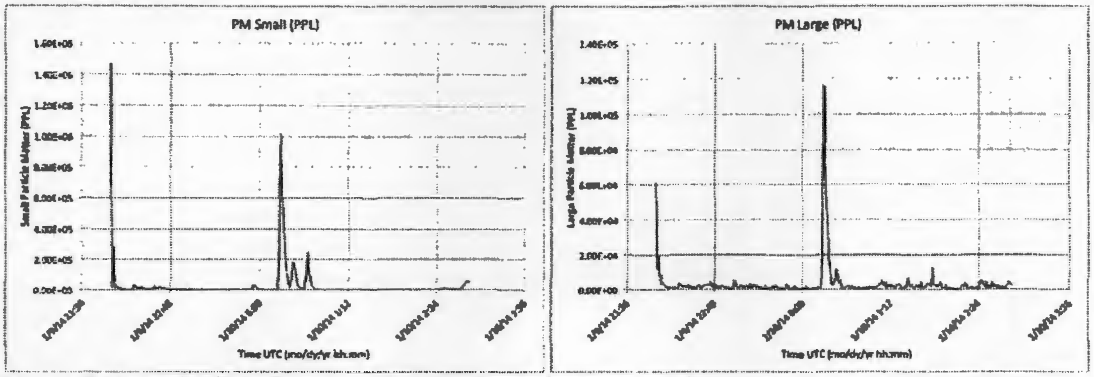

Figure 8. Particle data show small (<1um) and large (>1um).

CONCLUSIONS

Even though sensors for measuring particulate matter have been available for decades, there are still no readily available, cost effective particulate matter sensors suitable for incorporation into a wireless sensor network. To resolve this dilemma, we have designed and constructed a relatively inexpensive optical particle counter and incorporated it into a WSN. Operating independently or as part of a network of particle counters, our device provides data essential to understanding particulate matter exposure in both indoor and outdoor environments. Measurements obtained with the system are useful for applications including personal health impact awareness, dynamic particulate matter mapping, and airborne contamination movement within aircraft cabins.

ACKNOWLEDGEMENT

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