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Dense, Low-Power Sensor Network for Three-Dimensional Thermal Characterization of Large-Scale Atria Spaces

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Abstract— We describe the design and implementation of a dense, low-power wireless sensor network for fine-grained three-dimensional thermal characterization of a large open indoor space. To better understand the airflow dynamics and ensuing energy efficiency potential of this type of modern architectural design, we developed a sustainable wireless mesh network consisting of 50 sensors hung on an array of thin cables in a 210 m², 14.2 m tall atrium for real-time temperature and humidity monitoring. The goal is to create compact wireless measurement sensor blocks for dense coverage in the building. We demonstrate the implementation through a preliminary analysis, which includes the evaluation of temperature distribution discrepancies with computer-simulated results and data taken during natural ventilation to illustrate the nontrivial, well-mixed temperatures observed during the studies.

I. INTRODUCTION

The energy usage for heating, cooling and ventilation in a commercial building has a major impact on commercial energy consumption. However, most research on thermal characterization for energy efficiency focuses on monitoring energy use and system design of data centers, where the geometry of the space is simple and symmetric, and the heat sources (power lines and servers) are well confined. Although atria have already become a common feature of new building designs, the complex flows and heat transfer in atrium environments, such as turbulent natural convection or conjugate heat transfer from solar radiation, are not usually included as factors in energy simulation programs. Real-time data measurement for the validation of computational fluid dynamics simulations is critical to establish energy-efficient control matrices for building management systems [1]. However, full scale measurements [2] are rarely performed for customized building energy profiling. Our motivation is to create an easy-to-deploy wireless sensor system for real-time energy profiling and control feedback for building management systems. The work was inspired by the mobile measurement technology (MMT) from IBM Research [3-4], a measurement cart for rapid data gathering and customized modeling used to monitor and discover energy-saving

opportunities. Such systems are targeted for highly symmetric, cloistered spaces. However, for our purpose of evaluating and studying large-scale atria spaces, we need a wireless system that can be freely distributed throughout large open areas to gather three dimensional temperature and humidity data for finding energy saving opportunities and perform full-scale experiments, such as determining air flow and heat transfer distributions in atrium environments.

We have deployed a wireless environmental sensor network for three-dimensional thermal characterization of atria geometries. Each sensor unit is a standalone node capable of communicating with the others through a wireless mesh network and is set up as an end device. The data collected are forwarded from Zigbee router devices that are deployed around the outlets on surrounding walls.



Figure 1. Left: image of 65 wireless temperature/humidity sensors suspended with wires in 5 rows and three layers mapped to the corresponding floors in an atrium space.

Figure 1 shows the sensor with its perforated enclosure and the atrium space where we deployed our experiment. Each sensor was hung in midair on a 49-strand stainless steel cable. The sensors are 2.84 meters apart from each other in our setup.

II. METHOD AND EXPERIMENT

Our work began with the development of a low-power wireless sensor system. Each sensor node consists of a temperature sensor (LM35CZ) and a humidity sensor (HIH-4030) with individual microprocessor (ATMEGA 164), which controls the wireless data transmission and power management. Table 1 is the list of components in the hardware design. We calculated the power consumption of each component and operating modes assuming one sample every 3 minutes estimated that each node could run for 96.75 days with two 1.5V 2500mAh batteries. The performance could be drastically improved if the sampling rate was lower or a more efficient microprocessor and a properly duty-cycled temperature/humidity sensor was employed [5].

TABLE I. LIST OF COMPONENT AND POWER CONSUMPTION

Component	uA	Duty Cycle	uA	
LM35CA	91	1	91	8%
HIH-4030	200	1	200	19%
LDO	40	1	40	4%
MCU (active)	2100	0.0021	4	0%
MCU (Idle)	500	1	500	46%
Xbee - xmit	215000	0.0007	155	14%
Xbee - receive	55000	0.0013	76	7%
Xbee - idle	10	1	10	1%
Total:			1077	
Battery Life			96.75	days

We performed two studies with this system. The first was a natural ventilation test to evaluate the temperature distribution seen during steady-state and thermal ramp-up from a temperature shock created by turning on a large array of light bulbs placed on the atrium floor. The second study was aimed at comparing simulation results to the temperature distribution obtained using a simple 2-dimensional heat transfer model that interpolated the actual acquired temperature data.

A. Natural Ventilation Test

This system has been used to monitor a naturally ventilated atrium and observe the temperature distribution within the atrium under transient and steady state conditions. To control airflow through the four-story, 2980 m³ atrium, all openings to the atrium were sealed with plastic tarps and fire shutters except two openings on the first and third floor. Some

of these sealed openings are shown in Figure 2. The third floor opening leads to an auxiliary atrium that is open to the outdoors on the sixth (top) floor. All measurements were taken after 9 pm to eliminate the impact of solar gains on the atrium. A 6 kW array of 100 W incandescent light bulbs was used as a heat source in the middle of the atrium floor to create a temperature difference between the indoor and outdoor air. This temperature difference was intended to induce a buoyancy-driven flow to draw in air through the first floor and exhaust it through the third floor. However, strong winds on the sixth floor and conditioned air from an adjoining building that entered the auxiliary atrium drove the air downward through the third floor opening and out the first floor opening. As a result of this reverse flow, we were able to observe the relative strength of a plume over the 6 kW heat source in a flow dominated by inertial forces.

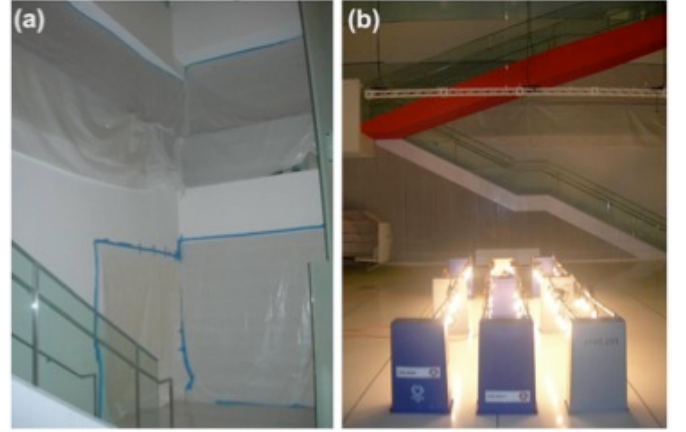


Figure 2. (a) Plastic tarps and fire shutters are used to seal all but two openings to the atrium during the natural ventilation experiment. (b) The 6 kW array of 100 W light bulbs that was used as a heat source in the middle of the atrium for creating a temperature difference between the indoor and outdoor air.

Our thermal measurement system provided a detailed temperature distribution within the atrium during the transient ramp-up period and after steady state conditions were reached. Surprisingly during both periods, no thermal plume was observed over the heat source. Thirty minutes after the heat source was turned on, no plume was detected in the atrium as shown in Figure 3. The temperature distribution was fairly uniform throughout the four-hour ramp up time. After steady state conditions were reached, the mean temperature was 24.0 C with a standard deviation of 0.68 C, which is slightly larger than the 0.50 C stated accuracy of the temperature sensors. This result was supported by a concurring series of discrete airflow measurements (see below).

In addition to providing insight into plume formation in naturally ventilated atria, this experiment illustrates how the thermal characterization system can shed light on non-trivial flow patterns and building conditions. Furthermore, the low power requirement allows the system to perform long term monitoring that can illuminate seasonal or annual trends within the building. More analysis has been done using this

data, including characterization of a large naturally-ventilated atrium through temperature readings, airflow measurements, detailed airflow visualization techniques, and particle image velocimetry [6].

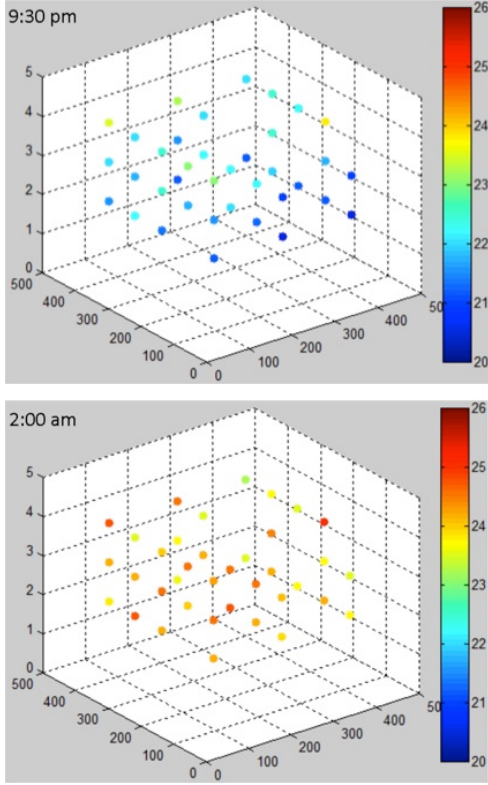


Figure 3. Top: Temperature distribution during the transient ramp-up period of the natural ventilation experiment. Bottom: Temperature distribution during the steady state period of the natural ventilation experiment.

B. Planar Thermal Interpolation

We also used our thermal data to compare an interpolated temperature distribution with computer-simulated results. Using the Partial Differential Equation (PDE) Toolbox in MATLAB [7], we created a two dimensional steady-state thermal model. The heat equation is a parabolic PDE as follows:

$$\rho C \frac{\partial T}{\partial t} - \nabla \cdot (\kappa \nabla T) = Q + h \cdot (T_{ext} - T)$$

Where ρ is density, C is heat capacity, κ coefficient of heat conduction, Q is the heat source and T_{ext} is external temperature. In our steady state model, we assumed that Q (heat source) coming from the HVAC system entering the control volume is equal to Q lost to the environment.

$$\rho C \frac{\partial T}{\partial t} = 0, \quad -\nabla \cdot (\kappa \nabla T) = 0$$

This assumption is achieved in the MATLAB PDE tool by setting h (convective coefficient, representing Q lost to the environment) equal to 0, along with Q (heat source, representing Q coming from the HVAC). Setting Q and h to 0 causes the system to depend only diffusion due to the boundary temperatures, such that k (conductivity) is no longer important. The equation is only depending on the divergence of the temperature gradient in the 2D space.

Figure 4 is an example of our two-dimensional temperature distribution analysis, where we simulate the heat transfer in vertical slices. To evaluate the thermal effect by airflow in the HVAC system we extracted sensor data for a particular point in time (± 3 min) from all sensors on each floor. We also took sensor readings from the boundaries at the edge of the atrium and used the PDE tool to create 2-D representation of the heat distribution of each floor slice (Figure 4(a)). We then compared the data with a linear interpolation of the real readings from all the sensors. In particular, we noted that the major percentage errors were associated with unmodeled dynamic boundary conditions, such as the supply and return flows on the first floor and wall boundaries at the top of the atrium (Figure 5). The mean error between the actual sensor data and the theoretical model based on steady state heat transfer was ± 0.23 degree Celsius. The maximum discrepancy happened on the second floor, where a vent is located, creating a difference of around $+0.9$ degree Celsius.

This approach establishes a quick way to estimate the continuous thermal profile and can provide instant feedback on the adjustment of airflow parameters for building HVAC management.

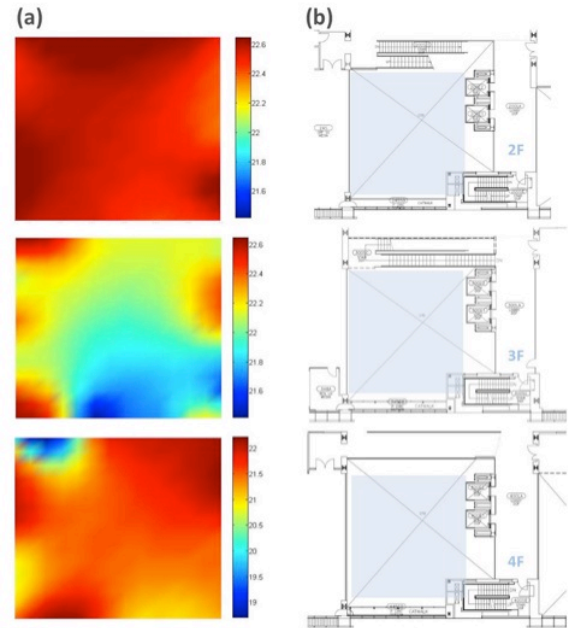


Figure 4. Two-dimensional temperature distribution analysis. (a) Thermal model of each floor based on boundary conditions defined by perimeter sensor data readings. (b) Floor plans of each layer, indicating the openings and structural perimeters at each floor.

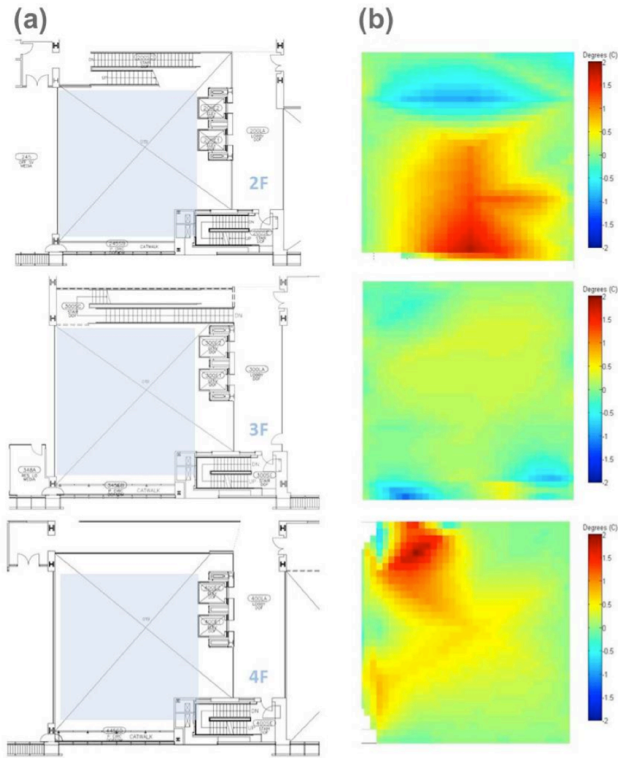


Figure 5. (a) Floor plans of each layer, indicating the openings and structural properties at each floor. (b) Differences (errors) between interpolated thermal sensor readings and our planar theoretical model.

III. SUMMARY AND DISCUSSION

In this paper, we described the design and implementation of a dense, low-power wireless sensor network for fine-grained three-dimensional thermal characterization of a large open indoor space. To better understand the energy efficiency of this type of modern architectural design, we developed a sustainable wireless mesh network hung on an array of thin cables in an atrium for real-time temperature and humidity monitoring. Two preliminary analyses are presented in this paper to demonstrate the capability of our network for measurements in large atria spaces.

Our first experiment monitored the spatial temperature distribution throughout a four-hour thermal ramp up and provided insight into plume formation in naturally ventilated atria with non-trivial flow patterns and realistic building conditions. We found the temperature distribution to stay fairly uniform throughout the four-hour ramp up time. After steady state conditions were reached, the mean temperature was 24.0 C with a standard deviation of 0.68 C, which is slightly larger than the 0.50 C stated accuracy of the temperature sensors.

The second study was aimed at evaluating the accuracy of only having measurements at the atrium perimeter under simple assumptions (steady state). We constructed simplified two-dimensional horizontal slices of the space and explored

the possibility of exploiting only minimum computing power with an adiabatic diffusion model (without needing a supercomputer for a full-up computational fluid dynamics (CFD) simulation) to infer the thermal behavior of the large three-dimensional space. The mean error between the actual sensor data and our theoretical model based on a steady-state heat transfer was ± 0.23 degree Celsius. The maximum discrepancy was around + 0.9 degree Celsius.

Both experiments showed promising results for using this mobile measurement system to provide instant feedback on the HVAC system. We have been continually archiving this data set since 2010 and integrating it with data from our building's HVAC system through a 3D sensor data visualizer and interactive browser produced by our research team called Doppellab [8].

Through different assumptions of the overall thermal behavior, we can evaluate the potential energy loss caused by the building architectural design and the effect of its HVAC system. More sophisticated models will be developed and tested across different seasons and times of day. Our future work will involve collecting more data and using this information to evaluate the effect of radiation, heat, and airflow on energy efficiency for different architectural designs. The next step includes adding more compact, low-cost sensors that can measure other parameters, such as airflow, to evaluate the impact of convection on heat transport and to compare the sensor readings with a full computational fluid dynamics (CFD) model, which is the gold-standard quantitative method used for evaluating thermal behavior in building HVAC systems.

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