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A simple model for automatic analysis and diagnosis of environmental thermal comfort in energy efficient buildings

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HIGHLIGHTS

- Mathematical model with fitted parameters describing key features of HVAC systems.
- Combined study of temperature, humidity and indoor CO_2 concentration in workplaces.
- Low-cost system for comfort analysis and modeling in smart energy platforms.

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ABSTRACT

We present a mathematical model to diagnose HVAC systems in buildings based upon the analysis of a small number of ambient state variables. In particular, the equations of the model accurately fit recorded data of temperature, relative humidity and carbon dioxide concentration in different workplaces. For validation, data were obtained under different conditions and with different sensors. In particular, we designed and fabricated a wireless sensor that measures and transmits data to a remote device and we also applied our model to data collected using a commercial sensor. For each case, information was obtained that could be used to understand and predict the evolution of ambient variables that impact thermal comfort and energy consumption in buildings. The tools presented here can thus be of great interest to achieve affordable, smart energy-efficient buildings, while adhering to environmental laws and comfort for work spaces.

1. Introduction

Presently, buildings account for approximately 40% of the global primary energy consumption [1]. In developed countries, HVAC systems (i.e. heating, ventilation and air conditioning) constitute one of the largest energy end-use sectors and represents nearly half of the total energy expenditure of buildings, especially in the case of non-domestic facilities [2]. Studies show that highly efficient HVAC systems can significantly reduce both the global energy demand and carbon dioxide emissions [3–8]. The optimization of environmental conditioning systems, can have a major impact on energy efficiency [9–12], operating costs [13,14], occupant comfort [15,16] and even economic value [17] of buildings, especially in the case of intelligent constructions [18,19].

The purpose of an HVAC system is to provide and control suitable ambient conditions. A combined analysis of temperature, relative humidity and CO_2 data, provides relevant information about the indoor environmental comfort as well as addressing issues related to ventilation rates, carbon dioxide concentration and health [20]. While poor ventilation can result in unacceptable levels of carbon dioxide, excessive ventilation leads to excessive energy consumption and frequent heating/cooling cycling to maintain a stable temperature [21]. Thus, assessing the suitability of HVAC systems [22] is important to avoid extra consumption costs [23]. One approach is to develop automatic tools that measure [24], diagnose [25] and predict [26] the performance of HVAC installations, with respect to the comfort provided and energy consumption. For this, an accurate mathematical model that correctly describes the dynamic response of the system to the relevant state variables is necessary for an optimal solution [27]. A recent review on different modeling methods for HVAC systems in relation with their impact in energy consumption can be found in [28].

An adequate monitoring system should balance quality and reliability with reduced costs [29]. Also, a simple implementation with an affordable and straightforward placement of the sensors

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is important [30,31]. Finally, precise mathematical tools are essential for accurately processing the collected data [32]. To achieve this goal, many different solutions have been proposed [33,34] including stochastic methods [35], identification techniques [36], ontological models [37], fuzzy linear regression [38] or dynamical simulations [39], amongst others [40–43].

Understanding with precision the dynamics of air which ultimately leads to the resulting indoor environmental conditions requires the usage of the powerful mathematical technique called computational fluid dynamics (CFD), see [44,45] for recent reviews. CFDs have been successfully applied to the study of air diffusion, ventilation, energy consumption simulation and thermal comfort, see *e.g.* [46]. However, CFDs are computationally costly and require using data of the building under study such as construction materials or the geometry of the rooms [47]. For the purpose of introducing control and automation systems in intelligent energetic platforms, the complexity of CFDs makes them hardly accessible to market competitive solutions. Thus, in this work we take a different view and present a simple parametric model to give an effective description of the evolution of ambient variables, with the goal of designing strategies that can be implemented with a lower cost. The model depends on a few basic assumptions about the physical processes involved and can be easily programmed in a remote sensor to process and interpret ambient data.

To demonstrate the validity of our model, we compared results using data collected under different configurations and sensors. For one data set, we used low-cost wireless sensors, manufactured with standard electronic components at the Optics Laboratory in Ourense (University of Vigo, Spain). Two such sensors were placed in different rooms (office and reception) located in a building in Panama City (Panama), and the temperature (T), relative humidity (RH) and carbon dioxide concentration (CO_2) were recorded. For another data set, we used a commercial sensor located in a building in A Coruña (Spain) under totally different external climatic conditions to measure the same variables over the same period. We show that for all cases studied, the model agrees with the data to high degree.

We begin in Section 2 with a description of the system and the conditions of operation. An analysis of the data of the office in Panama in view of the simple model is presented in Sections 3 and 4, where temperature, relative humidity and CO_2 concentration are subsequently discussed. Section 5 is devoted to considerations on the validity and limitations of our method. In particular, we study the data of the other two cases, for which it is essential to take into account the variation of outdoor conditions. Finally, before presenting our conclusions, we discuss how this kind of diagnostics can be used in combination with actuators to minimize energy expenditure while maintaining the spaces comfortable.

2. Description of the system

2.1. The detection system

The electronics of the designed device consists of an 8-bit microcontroller (μC), a relative humidity and temperature sensor chip, a CO_2 sensor and a radio transmission module based on *Xbee* technology. All the components were mounted on electronic boards designed and fabricated in the Optics Laboratory of the University of Vigo in Ourense (Spain). In Fig. 1 we show the transmission module (left) and the final placement together with the CO_2 detector (right). To power supply the device, lithium thionyl chloride batteries are used.

The temperature sensor is band gap based and its resolution is 0.01 °C with an accuracy of ±0.3 °C. The relative humidity detector is based on capacitive changes and it has a resolution of 0.04%RH while its accuracy is ±2.0%RH. Finally, the CO_2 device uses non-dispersive infrared (NDIR) principle to measure the concentration of this gas [48] and its resolution and accuracy in parts per million (ppm) are 5 ppm and ±50 ppm, respectively.

As we mentioned above, we have remotely monitored the temperature, relative humidity and carbon dioxide concentration. These data were collected every five minutes. Making more frequent measurements does not improve the quality of the data and is undesirable because the CO_2 sensor consumes a substantial amount of energy, limiting the life cycle of the batteries. To track the charge level of the battery, its voltage is sampled with the analog-to-digital converter (ADC) of the μC. A voltage divisor was implemented for this purpose. Afterwards, with an I2C communication protocol the temperature (in °C) and relative humidity (in %) values are read by the μC and temporally stored in its memory. Subsequently, the CO_2 sensor is turned on during 32 s, and then the carbon dioxide concentration value is measured in ppm and saved.

Once all the data have been received, the radio module is switched on and the data (including the sensor identifier, temperature, humidity, charge of the battery and CO_2 concentration) are sent as a character stream to a web server. A sketch is shown in Fig. 2. Finally, the radio module is turned off and the microcontroller enters in a sleep mode in order to save energy and reduce battery consumption. If needed, the time lapse between measurements can be changed in the EEPROM (electrically erasable programmable read-only memory) of the μC by reprogramming it.

The device is autonomous and can be easily installed just by hanging it on the wall.

2.2. A web–based platform

All the information collected by the sensors can be sent to a server and therefore instantaneously received through the internet anywhere in the world. A web platform for energy management of buildings called "*Equs*", previously developed [49] for monitoring, supervising and controlling environmental variables and energy consumptions, was used to collect and process the data (see Fig. 3).

We must stress that energy consumptions can also be tracked and controlled by means of *Equs*, as it includes a Supervisory Control and Data Acquisition (SCADA) system, to provide control of remote equipment and to improve data analysis. Another interesting alternative could be to program the microprocessor of the detector in order to include the code that can perform the data analysis and to transmit the results to a local computer or other kind of device like a smartphone or a tablet.

2.3. General considerations about the studied workplaces

To show a practical implementation of our model under realistic conditions, we studied three rooms located in two buildings in Panama and Spain. We monitored the most important variables related with environmental thermal comfort, i.e.: temperature (T) and relative humidity (RH) as well as indoor air quality by measuring carbon dioxide concentration (CO_2). All the measurements were taken every five minutes. For the analysis, we used a set of data from a period starting on September 1st, 2015 at 00:00 and ending on September 27th, 2015 at 10:10. This lapse of time includes working days as well as weekends and is large enough compared to the "basic cycle" of activity of the studied zones, which is one week. It would be interesting to consider larger periods and a greater number of sensors following the guidelines that we present here. That would be useful to refine the model parameters without modifying the general discussion. Our techniques can be easily extrapolated to analyze other important variables like