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# Virtual partition surface temperature sensor based on linear parametric model ☆

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## Highlights

- We propose a virtual partition surface temperature sensor for multi-zones.
- Physical law based linear parametric model is validated with off-control data.
- Sensitivity analysis using on-control data and three criteria is carried out.
- The sensor can support supervisory control for soft-repairing of device fighting.

## Abstract

Multi-zone structure is common in commercial office buildings, retail stores and supermarkets. Because there is no physical partition between zones, there could exist significant thermal impact among the adjacent zones than in other commercial buildings. It is critical to accurately analyze the energy interaction and reduce the modeling uncertainty for supporting advanced control. We propose a virtual partition surface temperature sensor for quantifying the variables and solve this challenge by using linear parametric models. The derived models based on physical law can be used as a guideline on selecting appropriate orders in mainly ARMAX (autoregressive moving average with exogenous variables) and/or ARX for improving the sensor's performance. Validation of the virtual temperature models is conducted by three validation criteria: goodness of fit ($G$), mean squared error (MSE) and coefficient of determination ($R^2$) under off-control conditions. The validation results show that the physical model based linear parametric model, ARX 211, performs well and similar to other system identification models, such as ARMAX 2111 and ARX 221, for estimating surface temperatures. The sensitivity analysis using three on-control conditions (under-sizing, proper-sizing and over-sizing condition) is conducted for analyzing and evaluating the performance and barriers of this virtual sensor. The proposed easy-to-implement model can be applied to support supervisory control of equipment in multi-zone buildings and other applications to supplement the measurements, like estimating the temperature of a structure integrated cooling or heating application in renewable energy areas.

## Introduction

Commercial buildings accounted for 19% of total energy consumption in the U.S. in 2009 [1]. Based on the existing data, it is expected that commercial building floor space can reach 109.8 billion sq ft in 2035, a 53% increase over 2003 level. From this estimation, this building type would consume significantly more energy than in 2009 [2]. Specifically, based on U.S. Commercial Sector Primary Energy, heating, ventilation, air-conditioning and refrigeration systems (HVAC&R) accounted for about 50% of the total energy use in commercial buildings. As one typical HVAC equipment, rooftop units (RTUs) have been intensively used in commercial buildings. They serve nearly 50% of all cooling conditioned commercial floor space in the U.S. [3]. Although the current low-level individual control of RTUs works fine in maintaining the space condition, it wastes much energy due to simultaneous cooling and heating, non-coordinated local control, and inherent oversizing effects [4]. The uncoordinated frequent on–off also deceases the life cycle of equipment, affects the indoor humidity and causes undesired interaction between RTUs and the refrigeration system in stores. Specifically for inherent oversizing, at least 15–25% (40% of surveyed RTUs were more than 25% oversized [5]) of the actual calculated capacity is over-designed to ensure adequate cool and heat in the hottest and coldest period. These factors result in excessive energy use and the degradation of equipment efficiency. Based on real-time trended data in supermarkets, the authors of this article found that the over-sized capacity of the RTUs has an average value of 84% for cooling and 299% for heating. The lowest peak energy penaly for 12 stores with 268 RTUs is 34.66 kW in a cooling mode and 25.14 kW in a heating mode, while the highest peak energy penalty goes to 226.41 kW in a cooling mode and 1375.99 kW in a heating mode [4].

To improve the energy efficiency, advanced controllers, such as multi-speed fan control, demand-controlled ventilation and multi-stage compressor control, have been developed and studied for existing RTUs. Using the results of simulation [6], these techniques can save between 16% and 56% energy depending upon the type of commercial buildings and climate conditions. However, these current techniques are difficult to penetrate the market because of a cost-effective issue and a long-term simple payback period (3–5-year). In addition, they cannot eliminate problems such as simultaneous cooling and heating and non-coordinated control of multiple RTUs. Fundamentally, the advanced retrofitting solutions are still individual control without analyzing and solving the inter-zone interactions between zones. The energy interaction could be affected by unsynchronized control operations between RTUs leading to simultaneous cooling and heating conditions and energy waste. In addition, the retrofitting solutions require experienced technicians for installation and routine preventive maintenances resulting in cost-effective issues.

To observe the simultaneous cooling and heating effect, sensors are required for measuring these energy interactions. Due to the characteristics of multi-zone structure, there are no actual partitions between zones and the sensors are not common in these surroundings. Therefore, virtual sensors being continuously developed in many areas such as HVAC and automotive areas may be applied to address this challenge. The concepts of virtual sensors can be categorized in three criteria [7]: measurement characteristics-based criterion (transient-state and steady-state data-based approach); modeling method-based criterion (white-box, gray-box and black-box models) and application purposes-based criterion (replacement and observing). For the first criterion, a steady-state based approach is typically applied to quickly model the process from changed inputs or slowly changed inputs of a system, so it is suitable for fault detection and diagnosis, which is theoretically desirable to quasi-static process. Examples can be found in the very recent literature for e.g. air flow rate [8], [9], virtual wall surface temperature [10], refrigerant charge [11]. In contrast to a steady-state method, the transient-state based approach using a transient model (e.g. the state-space model [12], [13]) to predict an immeasurable variable is typically appropriate for real-time feedback control or transient document used in fault detection and diagnosis (FDD). With these behaviors, fast system responses such as chemistry field [14] and food process [15] have applied transient virtual sensors to detect fast system changes due to existing faults for AFDD and to measure values cost-effectively for a feedback control system.

Based on transient-state based observing application using a white-box model, this present paper applies a heat balance equation to define virtual partition surface temperature for estimating the interaction happens at the boundary. In the model, it composes of heat convection between a measured room temperature and surface wall temperature, heat conduction from outdoor temperature through walls and windows and energy interaction between the current and adjacent zones. This novel virtual sensor can be potentially applied to estimate and reduce model uncertainties occurring in off-control zones, study the zone interaction between the current conditioned space and adjacent zones and support novel supervisory control.

The study is organized as follows: first, the building configuration and development of the physical based and other linear parametric models are explained. Then, the validation of the model is processed with simulated data obtained from building simulation platform based on off-control condition. To test the robustness and performance of the developed model, the sensitivity analysis of a virtual surface temperature is conducted through three on-control conditions: proper-sizing, over-sizing and under-sizing conditions. At the end, the contribution of this study is briefly discussed.

## Section snippets

## Building simulation configuration and model development

In commercial buildings such as retail stores, supermarkets and restaurants, suitable thermal comfort is needed to retain customers. Cooling and heating supplied by packaged HVAC equipment such as an RTU and heat pump can maintain a set-point room temperature corresponding to outdoor temperature variation. This section briefly explains essential information to define a model development for the virtual sensor. …

## Validation and comparison by the data of the off-control simulation

The prediction of the physical model based linear parametric equation is validated and compared to the linear parametric models (Eqs. (4), (5), (6), (7)) by using off-control conditions of the exemplary building.

In Fig. 3, the procedure of model parameter estimation, model validation and model sensitivity analysis is illustrated. Artificial TMY weather data in Miami, Florida USA is applied. The simulation data are collected at every one minute.

In real control applications, control outputs are …

## Sensitivity analysis

By using the RTU control characteristics, Woradechjumroen et al. [4] analyzed the inherent oversizing effect and proposed five levels of oversizing signature. The analysis technique was developed based on the three significant factors including: thermostat set-point, effect of dead band temperature (EDBT) and annual design conditions [15]. In the results of analysis, runtime fraction (RTF), on–off number per cycle (*N*) and maximum on–off number per cycle (*N*max) of an RTU compressor and/or gas …

## Conclusion, limitations and future work

This study develops the virtual wall surface temperature sensor using a heat balance equation based linear parametric model. The proposed model is trained and validated through the simulated data obtained from the building simulation platform using the weather in Miami, Florida, USA. The data periods used for validations are 12 h, one day and two days at the peak design conditions of cooling demand in July and of heating demand in March. The validated results based on off-control conditions are …

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…Meanwhile, it was found that transient virtual sensors should be needed for better accuracy, especially in the operation with low valve opening rates. Virtual sensors have been developed for indoor observation purposes for energy consumption [53,54], thermal comfort [53], air infiltration [55], occupant count [56], and local temperature [57,58]. These virtual sensors are usually intended to observe the targets that are difficult to measure using a single sensor [53,55,56,59], or augment sensing coverage from the building level to the zone level [53,54], or from the physical spot to spatial distribution (or another virtual spot) in a zone [57,58].…

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…Also, it is difficult to have sensor redundancy for each phenomenon [15]. Virtual sensing technologies [16] have been recently applied to various HVAC&R systems to overcome the limited environment in building sensor networks [17–20]. Virtual sensors, which are able to estimate various phenomena that are difficult or expensive to measure in building systems, can be mass-produced by using mathematical models along with other existing physical sensors.…

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> …With the virtual sensor method, various measurements that would require more expensive sensors, or phenomena that are impossible to measure, can be estimated using related physical sensors that are relatively low-cost. In areas where the number of sensors and degree of redundancy is insufficient, virtual sensor techniques [12–16] have been applied to HVAC&R systems. These are able to overcome problems associated with the limited number and the environment of working sensors, e.g., virtual partition surface temperature sensors [13], air temperature sensors of air-handling units [14], and virtual refrigerant charge and pressure sensors [15,16].…

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