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Contaminant event monitoring in multi-zone buildings using the state-space method

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ABSTRACT

The dispersion of contaminants from sources (events) inside a building can compromise the indoor air quality and influence the occupants' comfort, health, productivity and safety. Such events could be the result of an accident, faulty equipment or a planned attack. Under these safety-critical conditions, immediate event detection should be guaranteed and the proper actions should be taken to ensure the safety of the people. In this paper, we consider an event as a fault in the process that disturbs the normal system operation. This places the problem of contaminant event monitoring in the fault diagnosis framework of detection and isolation. A main contribution of this work is the development of the state-space method, based on multi-zone building models, that enables the use of advanced fault diagnosis tools for contaminant event monitoring. Specifically, in this paper, we develop estimator schemes with adaptive thresholds for the detection and isolation of a single contaminant source under conditions of noise and modeling uncertainty. We demonstrate our proposed formulation using a 2-zone illustration example and a more realistic 14-zone building setting.

1. Introduction

An Intelligent Building (IB) is a system that incorporates computer technology to autonomously govern and adapt the building environment in order to enhance operational and energy efficiency, cost effectiveness, improve occupants' comfort, productivity and safety, and increase system robustness and reliability [1,2]. Fault diagnosis methods have been successfully applied in the IB design in order to save energy and create a comfortable indoor environment. So far, most of the applied methods have concentrated on Heating Ventilation and Air Conditioning (HVAC) systems and their various components (see Ref. [3] and references therein).

The enhancement of energy efficiency and the improvement of occupants' comfort are very important under normal operating conditions. However, there are *safety-critical* situations, during which the lives of the inhabitants might be endangered, these include a fire or a dangerous substance introduced inside the building. A contaminant source can be the result of an accident (i.e., CO leakage from a faulty furnace) or a planned attack. Recent terrorist events and reports of potential hostile attacks with airborne chemical and biological agents (CBA) have created a crucial and world-wide concern for building and occupant safety. Distributed sensor networks have been widely used in buildings to monitor indoor environmental conditions such as air temperature, humidity and contaminant concentrations. Real-time-collected data can be used to alert the occupants and the appropriate authorities. Accurate and prompt identification of contaminant sources can help determine appropriate control solutions such as: (i) indicating safe rescue pathways and/or refugee spaces, (ii) isolating contaminated spaces and (iii) cleaning contaminant spaces by removing sources, ventilating and filtering air. Therefore, the accurate and prompt identification of safety-critical events should be an essential part of the IB design.

Contaminant event monitoring can be classified as an inverse reconstruction problem (i.e. given the system parameters and output, find out which input has led to this output). In Ref. [4], the

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related literature on the inverse tracking of pollutants in both groundwater and air fields, is categorized into three types: forward, backward and probability methods. The first two are deterministic and are, in general, applicable for a single instantaneous point source when previous information on source location and release time can be obtained. Probability methods on the other hand, estimate the probability associated with a certain event, for instance the probability of a pollutant to be located at a specific location. Two probability methods that have successfully been applied to the problem of contaminant source isolation in indoor building environments are (i) the Bayesian updating method [5] and (ii) the Adjoint probability method [6]. However, both of these methods require some form of prior knowledge in the results demonstrated so far, either in the form of a constructed scenario database before the event or concerning one of the source characteristics during the event (location or the time of release).

This paper proposes the state space method for the problem of contaminant event monitoring. In control engineering, a state space representation is a mathematical model of a physical system as a set of input, output and state variables related by first-order differential equations [7]. The state space representation (also known as the "time-domain approach") provides a convenient and compact way to model and analyze systems with multiple inputs and outputs. In our proposed formulation, the contaminant event source is treated the same way as a fault in the process which we would like to detect and isolate. This enables the application of advanced fault diagnosis tools to the problem of contaminant event monitoring. The proposed solution can effectively detect and isolate the contaminant source in real-time conditions without *any* prior information of the source characteristics (onset time, location and generation rate). In fact, these parameters are all estimated as part of our proposed detection and isolation scheme.

A main contribution of this paper is the development of the state-space method, based on multi-zone models, suitable for monitoring the Indoor Air Quality (IAQ) against the presence of contaminant sources in a building environment. Multi-zone models have been widely used in building environmental studies for predicting airflows and the resulting contaminant transport. Airborne contaminants disperse throughout the building in a very complex manner that depends on a number of factors: the nature of air-movements into, out-of and within the building system; the influence of HVAC systems; the possibility of removal by filtration, or contribution by generation of contaminants; and the possibility of chemical reaction, radio-chemical decay, settling, or sorption of contaminants [8]. Using multi-zone models within the state-space method, we seek to comprehensively model these phenomena and characterize the uncertainties involved. In addition, we take a first step toward modeling actuators that have an effect on the air-movements by changing the opening of leakage paths (such as doors and windows) or the flow intensity (e.g., an extractor fan or the supply of an air handling unit). These control actions can assist in the prompt detection and diagnosis as well as the accommodation of safety-critical events by isolating certain building zones and cleaning/filtering the air. The ultimate objective of this work is the development of a framework that would facilitate the utilization of advanced fault diagnosis and accommodation techniques [9,10] to intelligent building applications.

Another contribution of this work is the development of estimator schemes with adaptive thresholds for the detection and isolation of a single contaminant source under conditions of noise and modeling uncertainty. To achieve this, we first characterize the modeling uncertainties involved due to the changing wind direction, the wind speed and the variable leakage openings and calculate some bounds on them. The use of adaptive thresholds increases the sensitivity of the detection and isolation algorithms, while at the same time avoids the presence of false alarms in the system. Note that frequent false alarms in a system, in addition to creating discomfort and unnecessary panic to the occupants, can cause mistrust in the correct operation of the fault diagnosis mechanisms with catastrophic consequences. We use a 14-zone building scenario (referred to as the Holmes' house [11]) to illustrate the proposed method.

The rest of the paper is organized as follows. First, in Section 2, we present related work in air-flow and pollutant dispersion modeling, contaminant event monitoring and the state-space method applied to the indoor building environment. Then, in Section 3, we develop the state-space method for contaminant event monitoring and control based on a multi-zone modeling approach. Section 4 shows how the developed method can be applied to the problem of detection and isolation of a contaminant source in an indoor building environment through a 14-zone representative building scenario. Finally, Section 5 provides some concluding remarks and presents our plans for future work.

2. Related work

In this section we present related work in air-flow and pollutant dispersion modeling, contaminant event monitoring and the state-space method applied to monitoring the indoor building environment.

2.1. Air-flow and pollutant dispersion modeling

For indoor air and contaminant simulation there are two main modeling approaches: Computational Fluid Dynamics (CFD) and multi-zone.

CFD modeling involves numerically solving the conservation equations of mass, momentum, energy and species concentrations by dividing the space into a finite number of discrete cells and then using an iterative procedure to achieve a converged solution. It can provide the spatial distributions and temporal evolutions of air pressure, velocity, temperature, humidity, contaminants, and turbulence intensity. The degree of accuracy of the method comes at the expense of high computational overhead and depends on the correct representation of the boundary conditions, the solution grid, and the level of transient characteristics [12].

Multi-zone models, on the other hand, represent a building as a network of well-mixed zones. Temperature, humidity, air velocity and pollutant concentration are assumed uniform within one zone. Zones are connected by discrete flow paths such as doors, windows, wall cracks, ducts and hallways. In this framework, a zone may be an entire room or part of a room. The model predicts the flow parameters based on mass conservation and component interaction. Multi-zone models are computationally efficient and are able to consider numerous transient effects such as occupants coming and going, air handling units (AHUs) turning on and off and variable wind directions. However, they usually cannot represent detailed air-flow within a zone, or model bi-directional floor-to-floor flows, duct junctions, and transport delays.[1,2] The most popular multi-zone simulation programs are COMIS [13] by Lawrence Berkeley National Laboratory (LBNL) and CONTAM [14] by the US National Institute of Standards and Technology (NIST). One interesting area

[1] The capability of accounting for transport delays has been implemented in certain zone-models using "one-dimensional convection/diffusion" models (e.g. CONTAMW, version 2.4).

[2] There is also the possibility of dividing each physical zone into a number of sub-zones including specific flow zones (e.g., jets, plumes, heaters, and boundary layer zones). This modeling approach, called "zonal models" aims to provide a compromise between the simplicity of multi-zone and the calculation complexity of CFD.