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Security-oriented sensor placement in intelligent buildings

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ABSTRACT

Intelligent buildings are beginning to utilize sensor networks for monitoring and protecting indoor air quality against contamination events. This paper presents a methodology for determining where to install such sensors. In particular, a multi-objective optimization problem is formulated for minimizing the sensor cost, the average and the worst-case impact damage corresponding to a set of contamination event scenarios. Each contamination scenario is comprised of parameters characterized by some given probability distribution. Based on these distributions, a set of representative contamination scenarios is constructed through grid and random sampling, and the overall impact of each scenario is computed, thus providing a solution to the sensor placement problem. The proposed methodology is illustrated by two case studies, a simple building with five rooms and a realistic building with 14 rooms.

1. Introduction

Intelligent buildings are beginning to utilize networked sensors for monitoring the Indoor Air Quality (IAQ) by measuring temperature, humidity, carbon dioxide and many other parameters of interest throughout the building environment. This information can be utilized in order to better control the mechanical systems (rollers, blinds, doors and windows) and the electrical systems (heating, ventilation and air conditioning) to create a healthy and comfortable living environment while at the same time minimizing the amount of consumed energy. More critical, sensor information can be utilized to alert the occupants about the presence of dangerous contaminants in the building air. These contaminants may be the result of an accident (e.g., *Carbon Monoxide* leakage from a faulty furnace) or a malicious attack. Under these safety-critical situations, it becomes of paramount importance that the contaminant is promptly detected and localized so that appropriate control actions are taken to mitigate the damage and ensure the safety of the people.

The first step in designing such an IAQ sensor network is to decide the number, location and type of sensors to use. Ideally, it would be desirable to have sensors in every room of the building, measuring all different types of contaminants, but the cost and sophistication of most IAQ sensors today makes this an elusive goal (at least for a class of high-cost sensors). In this paper, it is assumed that a limited number of sensors are available, able to measure the concentration of the contaminants of interest. The overall objective is to develop a procedure for finding suitable locations for these sensors, in order to achieve the maximum possible security of the indoor building environment with the minimum cost.

Deciding where to install these sensors is in general a difficult task due to the complex and dynamic conditions of the indoor building environment. For example, a sensor placement solution designed for a wind blowing from the west and assuming fully open doors and windows will seize to be optimal if the wind changes direction or if we close some of the doors and windows. In fact, the optimal solution depends on a number of parameters like the wind direction and speed, the status of the various leakage paths (doors and windows openings), the contamination source properties (location, duration, release rate) and the people characteristics (average occupancy in each zone, inhalation rate). In the proposed approach, since most of these parameters are not known in advance, probability distributions are used to describe them, which incorporate the existing knowledge about the building environment and the contamination event. Then, a representative scenario set is constructed through grid and randomized sampling of the probability distributions.

Each of the different scenarios is simulated using a multi-zone formulation that has been developed in our previous work [1] together with CONTAM [2], a multi-zone building simulation software. For assessing the damage caused by each scenario (e.g., number of people infected) we calculate an impact metric based on

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the total amount of contaminant inhaled and depending on the number of people, their age and type of their activity within the building. Finally, for deciding on where to place the sensors we solve an optimization problem that may involve multiple objectives, for instance to minimize (i) the average impact damage, (ii) the worst-case impact damage and (iii) the cost/number of sensors.

The main contribution of this work is to present a design methodology for formulating and solving the sensor placement problem in intelligent buildings, based on a multi-zone state-space representation of the dispersion dynamics, by taking into account the impact dynamics and existing knowledge of the building environment and contaminant event parameters in the form of probability distributions. In general, compared to existing simpler methods, the proposed methodology can better handle more complex scenarios which involve many parameters and different optimization functions. Note that one of the novelties of this work is that the proposed approach takes into consideration the building usage, which is something that has not been considered in previous related works.

This work offers to the decision maker a useful tool that analyzes all the different parameters involved in the building environment and gives the most informed recommendations on where to place the available sensors, in order to effectively detect and localize contamination events, while taking security into consideration. The simulation results illustrate the proposed methodology on a realistic building scenario representing a typical house with 14 rooms, referred to as the “Holmes's house” [3].

The remaining of this paper is organized as follows: in Section 2, related work in the indoor air quality sensor networks and the general sensor placement problem is presented. In Section 3, the problem formulation is proposed which couples dispersion and impact dynamics. Furthermore, the section provides intuition on how to construct the contamination scenario set and formulate the multiple risk-objective optimization program. In Section 4, two case studies are presented to illustrate the effectiveness of the proposed algorithm. Finally, Section 5 concludes the paper and future work is discussed.

2. Related work

Indoor Air Quality sensor networks are typically designed based on empirical rules of thumb and simple guidelines which are often subjective. A common approach is to evenly distribute the sensors to cover the facility (assuming equal coverage areas for the sensors) without taking into account the building aerodynamics or any information about the building utilization. As indicated in [4], there is a lack of system-level research in scientific design and evaluation of sensor systems to meet the IAQ design goals. The need of design principles for IAQ in buildings including the architecture (topology, number and placement of sensors) is also highlighted in [5]. There have been a few attempts in the literature to address issues related to the indoor sensor placement problem. These can be classified into two categories according to the method employed for simulating the indoor building environment: those based on (i) Computational Fluid Dynamics (CFD) and those based on (ii) Multi-zone analysis.

In the first category, some CFD software tool is used to study the contaminant transport. In general, CFD techniques have the advantage of increased accuracy in modeling airflows and contaminant propagation. In [6], the optimal sensor locations were determined for detecting releases in a building by using a CFD tool to estimate the distribution of contaminants. In [7], CFD techniques were also applied to predict chemical and biological agent dispersion in an office complex for finding the best locations for sensors and for developing effective ventilation strategies. Similarly, in [8], a CFD software program was employed to study contaminant transport in a nine-row section of a Boeing 747 aircraft cabin with airborne contaminants released under different scenarios for determining the optimal number and location of sensors.

The second category involves multi-zone models for calculating the airflows and contaminant transportation under different scenarios followed by an optimization method for estimating the sensor locations. In [9], six attack scenarios for a small commercial building were simulated, and a genetic algorithm was applied for each attack scenario to optimize the sensor sensitivity, location, and number to achieve the best system behavior while minimizing system cost. In [10], the impact of zonal and multi-zone modeling techniques on indoor air protection systems was analyzed for a typical office environment and a large hall. The proposed methodology could also be considered under this category. Compared to the aforementioned work, our approach uses sampling from probability distributions and additionally considers changing environmental conditions, the building utilization and people distribution in constructing the different scenarios.

Closely related to sensor placement is also the problem of contaminant source isolation and identification. Some representative work in this area includes the Bayesian interpretation approach (see [11] and [12]), to assess the effect of various sensor characteristics on the overall system performance regarding the time needed to characterize the release (location, amount released and duration). The optimal sensor placement, however, was not investigated. Furthermore, in [13], an inverse modeling method was proposed (the adjoint probability) for designing the sensor network and identifying potential contaminant source locations. The sensor placement solution provided, however, depends on certain information about the source (location or release time) that need to be given *a priori*, making this approach more suitable for the case of mobile sensors. The problem of contaminant isolation was also investigated in our previous work [1] using a state-space multi-zone formulation.

The problem of selecting locations to install sensors for optimizing some parameters such as controllability or security, has also received significant interest from other research disciplines, such as operational research [14] and control systems [15]. In addition, significant research has been conducted by the water research community, for improving the security of water distribution networks from deliberate or accidental contaminations [16]. When a contaminant enters at some location in the network, it propagates along the water flow, and may affect the consumers who use the contaminated water. In [17], a security-oriented sensor placement problem formulation for water distribution systems was presented, considering multiple risk-objective functions, and a solution methodology was proposed based on evolutionary computation.

Compared to the existing work in the literature, to the best of our knowledge, the approach presented in this paper is the first to provide a formal mathematical treatment to the problem of sensor placement in buildings for minimizing the impact damage, while taking into account contamination scenario parameter variability and multiple risk objectives, and can be used for CFD and multi-zone models. However, in this work a multi-zone model is used to aid better understanding and to limit the computational efforts required to simulate multiple contaminant dispersion scenarios. In specific, the overall impact is a function of the contaminant concentration in the various zones as well as the people distribution and characteristics. To evaluate the overall impact, a finite set of contamination scenarios is considered taking into account the parameter probability distributions.

3. Design methodology

In this section, the sensor placement design methodology is described. The intuition behind the problem is to formulate and