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Building occupancy detection through sensor belief networks

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Abstract

Currently it is difficult to determine when and where people occupy a commercial building. Part of the difficulty arises from shortcomings in available sensor technology, but an even greater deficiency is the lack of analysis methods appropriate to the determination of occupancy. This paper describes a pilot study describing new sensing and data analysis techniques, applied to the determination of space occupancy. The central premise of the paper is that improved building operation with respect to energy management, security, and indoor environmental quality will be possible with better detection of building occupancy resolved in space and time. We developed and deployed a network of passive infrared occupancy sensors in two private offices, and applied analysis tools based on Bayesian probability theory to determine occupancy. Specifically, a class of graphical probability models, called belief networks, was applied to the occupancy data generated by the sensor network. The inference of primary importance is a probability distribution over the number of occupants and their locations in a building, given past and present sensor measurements. Inferences were computed for occupancy and its temporal persistence in individual offices as well as the persistence of sensor status. The raw sensor data were also used to calibrate the sensor belief network, including the occupancy transition matrix used in the Markov model, sensor sensitivity, and sensor failure models. This study shows that the belief network framework can be applied to the analysis of data streams from sensor networks, offering significant benefits to building operation compared to current practice.

Keywords: Occupancy detection; Commercial buildings; Bayesian probability theory; Belief networks; Sensor networks; Energy management; Building security

1. Introduction and problem statement

Knowing how many people occupy a building, and where they are located, is a key component of building energy management and security. Commercial, industrial and residential buildings often incorporate systems used to determine occupancy, however, relatively simple sensor technology and control algorithms limit the effectiveness of both energy management and security systems. Among the shortcomings of current occupancy detection systems are a reliance on a single occupancy sensor in a zone under control, a lack of data analysis of the measured sensor signals, and unnecessary switching due to the fact that the viewed area is not necessarily identical to the controlled area.

This paper describes results from a project to design, implement, validate, and prototype new technologies to monitor occupancy, control indoor environment services, and promote security in buildings. The overriding premise of this paper is that better building services can be facilitated through better sensing. We interpret better sensing to imply a greater wealth of information rather than simply more measured data, achieved by combining two complementary approaches to occupancy data collection and analysis:

- *Development of low-cost distributed and redundant sensor networks*. We believe that delivery and management of building indoor environment services (e.g., lighting, heating, air conditioning, security), will be improved if control systems are based on systems of multiple independent distributed occupancy detectors, instead of relying on single points of occupancy detection, and
- *Development of new analysis methods and control algorithms to treat data arising from distributed sensor networks*. Our approach to the analysis of information collected by multiple related and redundant sensors is based on Bayesian probability theory. In particular, we apply a class of graphical probability models, called belief networks, for the purposes of prediction, diagnosis, and calculation of the value of information in building systems, and apply this information to building control.

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In summary, we propose to replace expensive single occupancy detectors with simple data analysis with sensor networks that consist of multiple low-cost occupancy sensors and that make opportunistic use of pre-existing environmental sensor data such as carbon dioxide concentration and space relative humidity. These multiple sources of information are then fused together using probabilistic data analysis, creating virtual sensors which are more powerful than single physical sensors. More powerful in this context means that the proposed occupancy detection system behaves like the conventional system for common scenarios at a lower cost, yet provides more accurate assessment of occupancy for uncommon scenarios, i.e. those with low probabilities. In this study, we will make use of selected sources of additional occupancy information.

With occupancy accurately known, both in time and in space, it also becomes possible to develop operational strategies for building response to external or localized internal threats. As an example, occupancy information in large multistory buildings allows for the targeted allocation of emergency personnel and resources in situations where every second counts.

2. Current approaches to occupancy detection

Commercially available technologies currently deployed to detect occupancy for energy management and security are limited by relatively simple sensor data processing and control software: it is still a challenge to ensure that lights and other services are switched off when spaces are unoccupied.

These systems use passive infrared (PIR) and/or ultrasonic technologies, signaling space occupancy based on changes in the temperature or sound profile of the space. In energy management applications, the occupancy sensor functions as a timer, sending a signal to a switch that turns off electrical power after a defined period of time has elapsed during which no signal has been received from the detector (e.g., switch lights off when the space has been unoccupied for 5 min). In security applications, an ‘‘armed’’ system initiates a security call immediately upon receiving a signal from a single detector. In conventional systems, as soon as a signal is received, occupancy is assumed without further analysis of signals from the same sensor or taking into account any other available information. Moreover, current systems cannot differentiate at all between one or more occupants in a monitored space.

There is a growing literature that addresses the effectiveness of occupancy sensors for controlling office ambient lighting systems, and other studies have evaluated the effectiveness of occupancy-based switching for power management of office equipment [1–9]. This work discusses only the North American market, yet it shows that occupancy sensors reliably deliver significant energy and demand savings in infrequently or unpredictably occupied spaces, such as washrooms, stairwells, corridors, storage areas (e.g., [7]), and mail carrier sorting stations (e.g., [8]). Comparable savings have eluded general office applications, and occupancy sensors have not achieved as wide use as other energy-saving lighting technologies [9]. There are often significant differences between actual observed savings (up to 43% reductions) and industry estimated savings (up to 70% reductions) that result from the application of single point occupancy detection systems.

Commercial occupancy detectors do not always perform according to specification. For example, the National Lighting Product Information Program (NLPIP) Specifier Report on Occupancy Sensors described 23 commercially available occupancy detectors, and performance data for 18 of these devices. NLPIP showed that many of the detectors tested did not respond to a movement trigger occurring within the coverage area claimed for the device [10]. These performance failures can be traced to a design feature that affects all current occupancy detection systems. These systems attempt to regulate the lighting in a local area (i.e., a single workstation or private office), by responding to activity occurring over a larger area (i.e., several workstations or passersby in a corridor). The zone that is *viewed* or monitored by any single detector is usually larger than the zone *controlled by* that detector. For example, a single occupancy detector will often respond to the presence of passersby and/or air streams coming from office equipment cooling fans operating within the field of view of the detector. Energy savings will be compromised because the probability is low that the area viewed by a single detector will remain vacant long enough for the lights to be switched off. Consequently, lights in these areas are switched off less frequently than they would be in a washroom, for example. Further exacerbating this problem is the wide variation in office layouts, which means that a generic solution using current technology is unlikely.

The solution we propose to this set of challenges is to use multiple, inexpensive distributed detectors that together function as a system, rather than a single, more expensive detector. A system based on multiple distributed detectors, with appropriate analysis and control algorithms, will ensure that controllers more reliably respond to local conditions within the coverage area. Occupancy information must be present in some form. Instead of relying on fewer, more expensive sensors, we have chosen to deploy a greater number of simple sensors, and extract the occupancy information from these multiple sensors through a more complex inference algorithm.

This paper describes the development of a novel distributed occupancy detection system in a small sample of private offices and workstations, and associated data analysis strategies and methods. This occupancy detection system uses three traditional PIR occupancy sensors aimed at occupied areas in the work space. These three detectors were complemented by a sensor that determines when the telephone is off-hook (i.e., a telephone conversation is in progress). Each device provides an independent measurement of occupancy. Together, the combination of three measurements provides a converging and redundant sensor network.

Equally important as the physical sensor network is the analysis framework that is applied to these data to determine occupancy, described in the following section.

3. Occupancy detection through probabilistic inference

The essential problem in the inference of occupancy is not a lack of data, but rather the lack of means to analyze and make