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Review article

Leveraging existing occupancy-related data for optimal control of commercial office buildings: A review

Weiming Shen [a,*], Guy Newsham [a], Burak Gunay [a,b]

[a] Intelligent Building Operations, Construction Portfolio, National Research Council Canada, Ottawa, Ontario, Canada
[b] Civil and Environmental Engineering, Carleton University, Ottawa, Ontario, Canada

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ABSTRACT

A primary strategy for the energy-efficient operation of commercial office buildings is to deliver building services, including lighting, heating, ventilating, and air conditioning (HVAC), only when and where they are needed, in the amount that they are needed. Since such building services are usually delivered to provide occupants with satisfactory indoor conditions, it is important to accurately determine the occupancy of building spaces in real time as an input to optimal control. This paper first discusses the concepts of building occupancy resolution and accuracy and briefly reviews conventional (explicit) occupancy detection approaches. The focus of this paper is to review and classify emerging, potentially low-cost approaches to leveraging existing data streams that may be related to occupancy, usually referred to as implicit/ambient/soft sensing approaches. Based on a review and a comparison of related projects/systems (in terms of occupancy sensing type, resolution, accuracy, ground truth data collection method, demonstration scale, data fusion and control strategies) the paper presents the state-of-the-art of leveraging existing occupancy-related data for optimal control of commercial office buildings. It also briefly discusses technology trends, challenges, and future research directions.

Contents

* Corresponding author.
E-mail addresses: Weiming.Shen@nrc-cnrc.gc.ca (W. Shen), Guy.Newsham@nrc-cnrc.gc.ca (G. Newsham), Burak.Gunay@carleton.ca (B. Gunay).

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1. Introduction

According to United Nations Environment Programme's Sustainable Building and Climate Initiative (UNEP-SBCI), the building sector contributes up to 30% of global annual greenhouse gas emissions and consumes up to 40% of global energy [1]. Similar results were reported by the US Department of Energy [2]: buildings in the United States account for about 41% of national energy consumption. Among the total commercial building energy consumption in 2010, 39.6% was consumed by space heating, cooling and ventilation, 20.2% by lighting, 4.3% by water heating, and 30.5% by plug-in equipment loads. These systems and devices are essential to support commercial building operations and maintain occupant comfort. Among all the buildings, commercial office buildings are the largest in floor space and energy use in most countries [3].

It has been widely recognised that the key to saving energy in commercial office buildings is to deliver building services only when and where they are needed, in the amount that they are needed [4–6]. Since such building services are usually delivered to provide occupants with satisfactory indoor conditions, it is important to accurately determine the occupancy of building spaces in real time [7–9] in order to garner such energy savings. Therefore, occupancy detection has attracted a lot of attention for decades, particularly in the field of lighting control [10]; occupancy sensors have long-been deployed at the room level to save energy, primarily in electric lighting systems [11–14]. The potential for energy savings with HVAC (heating, ventilating, and air conditioning) systems is also emerging [15–22]. From these deployments, savings of 20–50% are typically reported. A study conducted by Gunay et al. [23] indicates that a 10–15% reduction in the space heating and cooling loads can be achieved just by applying individual temperature setback periods based on historical office occupancy patterns. Occupancy sensors for lighting systems have been mandated in certain space types in contemporary energy codes and standards (e.g., National Energy Code for Buildings in Canada [24], ASHRAE 90.1-2016 [25]). However, penetration of these technologies as retrofits in all eligible spaces in existing commercial buildings is low, and first cost remains a tangible barrier.

One possible solution that is emerging is to leverage data from existing systems, installed for some other purposes, to provide an indication of occupancy. According to two studies [26,27], significant energy savings can be achieved by using the existing IT (Information Technology) infrastructure to enable energy savings in both IT (computers and networking) and non-IT infrastructure. Such occupancy information can be used by building control systems to reduce the energy consumption of lighting, HVAC, and other building systems [28,29]. Occupancy detection can provide information to these building systems to allow them to operate proportional to the number of occupants in the building [26,30] and ultimately to optimize the building energy management through integrated optimal control of active and passive heating, cooling, lighting, shading, and ventilation systems [31].

In addition to direct energy and cost savings through real-time intelligent control of HVAC, lighting, and plug loads, detailed and accurate occupancy information may also be leveraged for other energy-saving applications, including occupant engagement and behavior adjustment [32], achieving optimal demand response [33], optimizing energy storage, improving building energy simulation [34], enhancing building space modeling and utilization [35], supporting building planning and evacuation [36], and increasing building energy use forecasting accuracy [37]. Finally, there is some potential to lower building operation and maintenance costs. A study by the Electrical Power Research Institute (EPRI) found that while the increased on/off switching by occupancy sensors reduced fluorescent lamp life from 34,000 to 30,000 h, it also dramatically increased lamp longevity (time in the socket between replacements) from 3.9 years for always-on lamps to 6.8 years by not wasting lamp life during unoccupied hours [38].[1]

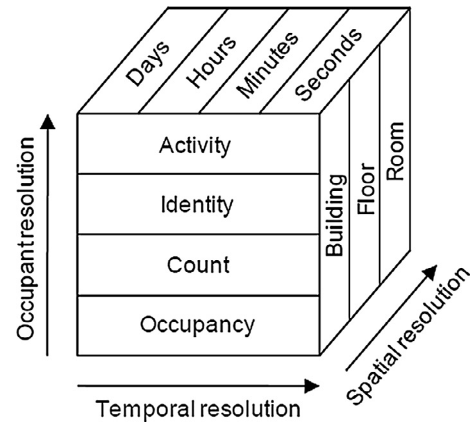

Fig. 1. Occupancy resolution in three dimensions (modified from Melfi et al. [26]).

The objective of this paper is to review and classify emerging, potentially low-cost approaches to leveraging existing data streams that may be related to occupancy, usually referred to as implicit/ambient/soft sensing approaches. The rest of this paper is organized as follows. Section 2 defines building occupancy resolution and accuracy. Section 3 reviews conventional occupancy detection approaches. In addition, illustrative examples from the literature were provided to demonstrate the strengths and the weaknesses of these occupancy detection approaches. Section 4 provides a comprehensive review of implicit/ambient/soft sensor approaches. Section 5 presents some concluding remarks and briefly discusses future research and development directions.

2. Building occupancy resolution and accuracy

2.1. Building occupancy resolution

Different applications require different levels of building occupancy resolution and accuracy. Melfi et al. [26] proposed to measure the occupancy resolution in three dimensions (as shown in Fig. 1):

- Spatial (zone) resolution: Building, Floor, Room
- Temporal resolution: Day, Hour, Minute, Second
- Occupancy resolution:
  - Level 1: Occupancy: at least one person in a zone
  - Level 2: Count: how many people are in a zone
  - Level 3: Identity: who they are
  - Level 4: Activity: what they are doing

Another level (Level 5) may also be added to track where an occupant was before, as suggested by Labeodan et al. [39]. Such Level 5 information indicates the particular occupant's movement history across different zones in the building and is essential in the design of proactive comfort systems [40,41]. However, this review focuses on the first four levels only.

A room typically refers to a single office or a space with four full-height walls (e.g., an office or a conference room) or a large zone containing many cubicles. In the context of this paper, we also

[1] LED lighting technology lifetime is largely impervious to switching frequency, rendering this trade-off less important in new installations.