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Review

Categorization framework and survey of occupancy sensing systems

Mikkel Baun Kjærgaard *, Fisayo Caleb Sangogboye

Center for Energy Informatics, Mærsk McKinney Møller Institute, University of Southern Denmark, Campusvej 55, 5230 Odense M, Denmark

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ABSTRACT

A large share of the energy usage in buildings is driven by occupancy behavior. To minimize this usage, it is important to gather accurate information about occupants' behavior and to improve sensing systems for gathering such information. However, as research on occupancy sensing systems goes beyond *basic methods* with an increasing diversification, there is a clear need to enable adequate comparison of these systems and their properties. The systems which differ in methods and properties also lack a categorization framework for classifying different options. This article proposes a categorization framework constructed from analyzing and comparing existing sensing systems to address these needs. The classification framework is being constructed from a literature survey of 51 papers and articles presenting 46 different occupancy sensing systems. It is intended that this framework can enable developers to better benchmark and evaluate sensing system, enable organizations to identify trade-offs for adopting sensing systems and aid researchers in scoping out future research in the area.

Contents

* Corresponding author.
E-mail addresses: mbkj@mmmi.sdu.dk (M.B. Kjærgaard), fsan@mmmi.sdu.dk (F.C. Sangogboye).

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1. Introduction

Improving the energy performance of buildings is crucial towards realizing a more sustainable society. One important challenge for improving the energy performance is the impact of occupancy behavior [1]. Occupancy behavior here refers to *all actions of the occupant (including presence) that affect building energy consumption* [2]. Occupancy behavior hugely influences the energy performance of both individual appliances and building-wide infrastructures. Individual appliances may include IT devices, kitchen facilities and production equipment. While building-wide infrastructures usually include lighting, heating, ventilation, cooling, IT, fire protection, security and water. Three agendas have been established towards addressing the impact of occupancy behavior: (A) replace equipment and infrastructures in buildings with more efficient ones in a manner that the same occupancy behavior results in a lower energy consumption. (B) engage occupants in changing their behaviors to less energy-consuming behaviors. (C) improve the intelligence of infrastructures and equipment to only provide needed utilities and comfort for the actual behavior of occupants. A typical example is to control ventilation with respect to estimated or measured occupancy rates [3]. In all three cases it is important to be able to gather quantitative information about occupant's behavior as follows: in case (A) to document savings in relation to occupancy behavior; in case (B) to provide feedback to support behavior change; and in case (C) to use occupancy behavior to optimize control.

To gather such quantitative occupancy information a wide range of occupancy sensing systems has been proposed in research and commercialized. In this article we refer to occupancy behavior sensing systems as *systems that measure, estimate, model and predict occupancy behavior based on inputs from pervasive sensing infrastructures*. Examples include systems for presence detection using PIR sensors, visual, stereo and thermal camera-based systems for counting people, and systems based on sensor-instrumented spaces to recognize the activities of individuals.

When surveying occupancy sensing systems for comparison, one has to answer many different questions. How do systems differ in types of occupancy information provided? What is the relation between the system and occupants? What is the spatial and temporal coverage; does the system allow for prediction of future occupancy situations? What types of sensor strategies are applied; are environments, objects or persons augmented? What types of methods and models are utilized? What is the resulting accuracy? These questions are important both for customers, developers and researchers who need to understand different design options and trade offs. It is believed that a categorization framework that takes cognizance of these questions can aid customers, developers and researchers to better survey, compare, and design occupancy sensing systems. This is especially important as developments in the field transit from understanding the basic mechanisms to combining different sensor strategies and modalities for providing information on complex behavioral patterns of occupants. The categorization framework can also aid researchers in scoping out future research in the area of occupancy sensing systems.

Existing surveys on occupancy sensing systems [4,1] have so far not presented a comprehensive categorization framework for the area. Therefore, this article proposes a comprehensive categorization framework for occupancy sensing systems that is constructed based on a literature study of 51 papers and articles. The 51 papers and articles propose 46 different systems which are analyzed and grouped according to the methods and techniques utilized to form categories for this framework. The classifications of four systems are presented in detail as examples. The classifications of all the 46 systems are available from our online repository [5] and presented on the associated webpage.[1] We present an analysis of the classifications and duly highlight evaluation metrics and unexplored design options. In this article we motivate the use of occupancy sensing systems in the area of energy performance, however, there are many other application areas for such systems including safety and evacuation, building utilization and customer profiling.

2. Categorization framework

The proposed categorization framework formulates nine categories. These categories are partly inspired by earlier works on occupancy behavior that are derived from the conducted literature study. This study was conducted by searching for key terms in relevant journals and conferences. The identified categories include and are defined as follows:

Information Type: types of occupancy information.
Occupant Relation: relation between the system and occupants.
Sensing Strategy: strategy for placement of sensors for observing occupancy behavior.
Spatial Granularity: characterization of the spatial resolution.
Temporal Granularity: characterization of the temporal resolution.
Spatial Coverage: characterization of the spatial extent.
Temporal Coverage: characterization of the temporal extent.
Sensor Modality: sensor modalities for collecting data about occupancy behavior.
Methods and Models: methods and models for processing sensing data to estimate and predict occupancy information.

[1] https://github.com/mbkj/OccupancySurvey/wiki.

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