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Real-time activity recognition for energy efficiency in buildings

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HIGHLIGHTS

- An unsupervised framework to detect activities and potential savings in real-time.
- Eliminating the need for collecting labeled activity data for training while achieving a high performance.
- Three sub-algorithms for action detection, activity recognition and waste estimation.
- Experimental validation in a testbed office with five occupants and two single-occupancy apartments.
- The framework could potentially be integrated with automation module for appliance control.

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ABSTRACT

More than half of the electricity in residential and commercial buildings is consumed by lighting systems and appliances. Consumption by these service systems is directly associated with occupant activities. By recognizing activities and identifying the associated possible energy savings, more effective strategies can be developed to design better buildings and automation systems. In line with this motivation, using inductive and deductive reasoning, we introduce a framework to detect occupant activities and potential wasted energy consumption and peak-hour usage that could be shifted to non-peak hours in real-time. Our framework consists of three sub-algorithms for action detection, activity recognition and waste estimation. As the real-time input, the action detection algorithm receives the data from the sensing system, consisting of plug meters and sensors, to detect the occurred actions (e.g., turning on an appliance) via our unsupervised clustering models. Detected actions are then used by the activity recognition algorithm to recognize the activities (e.g., preparing food) through semantic reasoning on our constructed ontology. Based on the recognized activities, the waste estimation algorithm identifies the potential waste and estimates the potential savings. To evaluate the performance of our framework, an experimental study was carried out in an office with five occupants and in two single-occupancy apartments for two weeks. Following the experiment, the performance of the action detection and activity recognition algorithms was evaluated using the ground truth labels for actions and activities. Average accuracy was 97.6% for action detection using Gaussian Mixture Model with Principal Components Analysis and 96.7% for activity recognition. In addition, 35.5% of the consumption of an appliance or lighting system in average was identified as potential savings.

1. Introduction

The United States is the second largest electricity consumer in the world [1]. More than 70% of the electricity in the United States is consumed by residential and commercial buildings, with each sector using roughly the same amount of electricity. Among the energy consuming service systems in buildings, lighting systems and appliances (e.g., computers, office equipment, televisions, other electronic devices, clothes washers, dryers, dishwashers, and cooking appliances) together contribute to more than half of the electricity consumption in residential and commercial buildings (i.e., 55% in residential buildings [2] and 51% in commercial buildings [3]). In addition, Miscellaneous

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Electric Loads (MELs), including both plug loads and hard-wired loads, are projected to increase from 6.1 to 6.9 Quads (13% growth) in residential buildings, and from 6.5 to 8.3 Quads (27% growth) in commercial buildings between 2016 and 2030, while non-MELs building loads are projected to decrease [1].

Due to the significant contribution of lighting systems and appliances to the total electricity consumption of buildings, there has been an increasing worldwide interest to find solutions to improve the energy efficiency of these service systems. Towards this end, several approaches have been developed that are based on encouraging occupants to change their wasteful behavior by making them aware of their personalized and detailed energy consumptions (e.g., [4,5]). Although these approaches could potentially result in a remarkable increase in buildings' energy efficiency, the savings depend on the conscious actions of occupants or change of occupant behavior, which is not always aligned with occupants' convenience [6]. To overcome this obstacle, other approaches have been developed that are based on automating the operation of service systems in buildings to be more energy efficient without requiring any behavior change in occupants (e.g., [7–9]). To better understand these two types of approaches, let's assume a scenario where an occupant can potentially save considerable amount of energy in long term by turning off the lights when they are not needed. Here, the potential energy savings can be achieved either by encouraging the occupant to modify his/her behavior to turn off the lights manually, or by an automation system, which turns off the lights whenever it recognizes there is no need. Although these two types of approaches are different in nature, they both require detailed insight into energy consumption. In response to this, various techniques have been successfully used to measure electricity consumption down to the device (i.e., lighting fixture and appliance) level to distinguish inefficient devices [10–12]. However, deeper investigations of energy consumption in buildings have revealed that occupant behavior in operating these service systems has significant impacts on a building's energy consumption and hence building controls [13,14]. In the context of improving energy efficiency of lighting systems and appliances, occupant behavior can be defined as the ways these service systems are used by occupants during their activities. Accordingly, recognizing activities could be an excellent venue to obtain the required insight on occupant behavior, based on which it is possible to detect potential energy savings to give feedback to occupants or generate automation commands for more efficient operation of these service systems.

With the activity recognition techniques, activities are detected either online, using real-time or streaming data, or offline, using historical data. Unlike in offline activity where activities are detected when they are completed, in online activity recognition, activities are detected while they are being performed. Therefore, at the time of recognition, in offline activity recognition, the sensing data that describe the activities are completely observed, whereas in online activity recognition, the sensing data that describe the activities is partially observed. In other words, regardless of the sampling rate, the sensing data that can be captured from uncompleted activities contain less information about the activities compared to the sensing data captured from completed activities. This makes online activity recognition a more challenging problem compared to the offline activity recognition. With the ever-accelerating pace of modern life, innovative automation systems that are intelligent enough to understand users' needs and accordingly take care of the tasks related to a building's life-cycle, from construction to operation, are needed more than ever (e.g., [15–20]). Along this line, for the sake of using activity recognition to develop an automation system that is capable of actively executing appropriate automation actions based on occupant's current activities in building, activities must be recognized in real-time (e.g., in seconds). Furthermore, to decide on the appropriate automation actions, activity recognition should be enhanced with certain contextual information to detect potential waste and savings. In this paper, we define waste as energy consumption of activities that could be potentially eliminated and peak- hour energy usage that could be potentially shifted to non-peak hours, which in turn results in performing the activities in a more cost and energy efficient manner. The insight on waste is needed not only for deciding on appropriate automation commands, but it could also enhance the process of identifying occupant's context-based automation preferences and assist them to make more informed decisions [21]. Existing well-performed online activity recognition approaches are majorly supervised and require labeled data for training, which put the burden on users. Moreover, these approaches do not offer a formal procedure for waste detection that could be potentially used for generating activity-based automation commands based on occupant preferences.

In line with the explained motivation above, in this paper, we introduce a novel framework to detect occupant activities and associated potential waste in real-time (within seconds), using an unsupervised hybrid approach based on inductive and deductive reasoning. In contrast to the commonly used activity recognition approaches that require manually labeled activity data for training (e.g., [22,23]), our approach is unsupervised and hence could be more easily adopted by occupants in real-world implementations. In addition, the presented approach in this paper provides a potentially adaptive and scalable modular platform that could be further integrated with an automation module that controls the operation of service systems in buildings to improve energy efficiency while meeting occupant convenience. The main contributions of this study can be summarized as follows: (1) introduction of an unsupervised framework to recognize user activities (that are relevant to building automation applications) in real-time; (2) reduction of burden on users by eliminating the need for collecting annotated activity data for training; (3) introduction of a formal procedure to detect potential waste that could be used to improve energy efficiency in buildings through an intelligent activity-based automation; and (4) real-world implementation of the framework in both commercial and residential test-beds. Following the summary of related studies in Section 2, the details of our framework are provided in Section 3. Next, the experiment, results and discussion are presented in Sections 4–6, respectively. Limitations of the study and potential future work are presented in Section 7. Finally, Section 8 concludes the paper.

2. Related prior work

Activity recognition has long been used to provide services related to healthcare and well-being (e.g., recognizing the progress of diseases or detecting emergency situations (e.g., [24,25]) via monitoring certain daily activities of patients or detecting one's physical movements, such as walking or falling. Since activity recognition techniques highly depend on the application area and hence activities of interest, the techniques that are appropriate for healthcare applications are not necessarily suitable for applications in other domains. Thus, more recently, activity recognition approaches have been investigated by researchers in the energy management domain to improve energy efficiency of buildings. Along this direction, a number of studies (e.g., [26,27]) have been conducted to create probabilistic models of activities and their associated electricity consumptions using historical time use and ownership data sets, which, as a result, do not reflect precise personalized consumption patterns. To overcome this issue, more recent studies have focused on recognizing activities using visual and sensing data captured from a building and its occupants. Relying on sensing techniques, these studies aimed at developing activity recognition approaches for either generating personalized activity-based energy consumption feedback (e.g., [28–31]) or controlling service systems in buildings via offering an activity-based building automation system (e.g., [32–34]). These approaches for activity recognition are mainly supervised (meaning that labeled activity data for training is required) or offline (meaning that activities are detected based on pre-segmented activity sequences and not on streaming sensing data in real-time). Moreover, the activity sequences, on which these approaches