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User activity recognition for energy saving in smart homes

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ABSTRACT

Energy demand in typical home environments accounts for a significant fraction of the overall consumption in industrialized countries. In such context, the heterogeneity of the involved devices, and the non negligible influence of the human factor make the optimization of energy use a challenging task; effective automated approaches must take into account basic information about users, such as the prediction of their course of actions.

Our proposal consists in learning customized structural models for common user activities for predicting the trend of energy consumption; the approach aims to lower energy demand in the proximity of predicted peak loads so as to keep the overall consumption within a predefined range, thus minimizing the impact on the end users. In order to build the models, the inherent recursive structure of user activities is abstracted from raw sensor readings, via an approach based on information theory. Experimental assessment based on publicly available datasets and synthesized consumption models is provided to show the effectiveness of our proposal.

1. Introduction

The ever-increasing energy demand in recent years is becoming a major issue as it represents a possible drawback in our society's future development, where energy is arguably the single most valuable good. Current consumption trends are unsustainable from an environmental point of view, and efficient usage and overall energy demand reduction have become two major concerns of the international community and most governments, due to both economic and environmental motivations [1]. Namely, according to the classical market laws, those trends have caused a burst in energy price which eventually has attracted greater attention to the energy problem.

The periodical shortages in energy supply during the last century, led to the birth of new research areas, and considerable effort is being carried out to devise viable solutions to the energy issue, ranging from discovering new energy sources to raising people awareness. In this context, a steady attention has been devoted to energy saving in buildings, starting from the energy crises of the 1970s [2,3].

User habits play a central role in household energy demand: an inefficient control of electric appliance and heating systems is a major energy waste source. Current literature about building automation, however, shows that building control is still mainly performed manually, as in the case of artificial lighting setting, powering appliances, or seasonal control of heating systems; additionally, automation in buildings has historically focused on narrow-scope tasks, such as lighting control with simple motion detection and a fixed timeout, or indoor climate control based on temperature and CO_2 level. On the other hand, user activities and behavior have considerable impact on the amount of consumed energy in all kinds of

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buildings (i.e., residential, office, and retail sectors). Thus, the design of *Building Energy and Comfort Management* (BECM) [4] systems has grown to become a self-standing research area, in order to optimize energy use in home scenario. A significant amount of the energy dissipated in these areas can be saved by fine-tuning deployed devices and appliances according to actual user needs; for instance, many research efforts have been focused on proposing "smart thermostats" based on occupancy prediction, or on maximizing user comfort by providing appropriate artificial lighting, based on the activity carried on at a given moment.

This research area belongs to the greater field of *Ambient Intelligence* (AmI), which encompasses different topics, ranging from environmental monitoring [5] to healthcare [6]; however, while the general scope of AmI is to apply artificial intelligence techniques to transparently support users in their everyday activities, a BECM system can be defined more specifically as a control system that uses artificial intelligence and a distributed sensor network for monitoring a building in order to ensure efficient usage of the available energy sources. A system implementing this approach must be able to predict the users' course of actions, in order to cope with the issue of reducing energy consumption without negatively affecting the user experience. Keeping intrusiveness at a minimum is essential to promote this kind of systems and to allow acceptance by a broad target of users; in fact, their impact on energy consumption will be significant only if they are used at a large scale. Several studies (e.g. [7]) have shown that a user-centric optimization of energy consumption, with no perceivable effects on user comfort, can lead to significant energy saving. In other words, the primary goal of energy saving systems is to automatically adapt to user preferences; this motivated us to follow the AmI paradigm, which requires minimizing user intervention, by "hiding" the system within the surrounding environment, while still enabling support to the users for their everyday-life activities.

Our main focus has thus been on adaptiveness, and our efforts have been specifically directed towards learning and prediction of user activities, as a first step towards an effective approach to energy saving. The present work is an extension of a previous paper, whose focus was the minimization of energy consumption in a home setting by preventing peak demands from exceeding a given threshold [8]. Our approach is based on discovering everyday activities performed by the occupants, and building predictive models for them; while retaining the fundamental focus of the original work, this paper provides a deeper insight into the issue of activity representation and of reliable simulation, and describes a new perspective to modeling user habits by a more efficient coding. In our vision, activities are inherently complex recursive structures; activity recognition may thus be formulated as a data mining task, so that the hidden structure may be identified and reconstructed by means of an unsupervised bottom-up technique based on frequent pattern analysis. This allows us to characterize the features of elementary constituting blocks for an activity, and to hierarchically combine them into more complex objects. A potential drawback of this approach is the computational cost related to building activity models from raw sensor data, and to matching them to newly acquired ones. Our current proposal processes sensory data by considering a description explicitly revealing their hidden structure, by way of a tree-like coding; moreover, we analyze the issue of producing a reliable simulation of the energy footprint of user activities, in order to obtain a more realistic model of energy consumption, and we assess our proposal by considering a new method for energy saving, in a realistic domestic environment.

The remainder of the paper is organized as follows. Section 2 summarizes some of the approaches presented in literature, as regards energy management, activity recognition in smart homes, and energy profile simulation. Sections 3 and 4 present our improved approach to energy saving, highlighting the novelty with respect to [8]. Section 5 provides experimental assessment of our system in comparison to the previous one. Finally, some final considerations are provided in Section 6.

2. Related work

Substantial research effort has been devoted to address the complex issues related to the design of a BECM system, and most proposals agree on the need for automated approaches to energy demand optimization; the presence of peaks in energy demand is often regarded as a symptom of a suboptimal scheduling of the use of electric appliances and the authors of [9–11], for instance, point out that even straightforward approaches, such as turning off unused devices, can be very effective in terms of energy saving. The challenging aspect of those proposals is their potential impact on user perception: if automated energy saving policies are so intrusive as to become a hindrance to the overall user experience, they might hardly be accepted from householders.

The key to designing a system capable of adapting to its users' needs is to correctly identify their activities. This is in fact a widely discussed topic in scientific literature, and common proposals include methods based on the use of logic, probabilistic methods, methods based on common sense reasoning, and, finally, data mining approaches; a detailed taxonomy is reported and discussed in [8]. Several state-of-art proposals assume the availability of considerable *a priori* knowledge, which makes them often prone to overfitting. Results obtained by these systems depend on the particular features of the application scenario, and their activity models are fitted onto data, as opposed to "emerging" from data itself [12]; this may be a major issue, if the goal is the design of a fully adaptive and generalizable system. Our work is partly inspired to the key ideas presented in [13,14]. The authors of [13], in particular, proceeding from a scenario characterized by scarcity of labeled data and uncertainty about activity granularity, showed that *formal grammars* are suitable to capture the inherent structure of activities. Their system, called Helix, initially generates a vocabulary combining unlabeled sensor readings, and attempts to incrementally merge them, by grouping similar activities into high-level ones. Grammar induction is used as a tool for heterogeneous sensor fusion in order to build up the structure of activities; each activity is regarded as a cluster in a multi dimensional space where the data streams coming from the different sensors present in the monitored area are