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Practical occupancy detection for programmable and smart thermostats

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HIGHLIGHTS

- Walkway Sensing as a new principle for using motion sensors to infer occupancy.
- It relies on motion sensors to only detect occupancy in the walkways between zones.
- Walkway sensing is converted into a reliable form of zone occupancy detection.
- The detection model called WalkSense operates in two modes of offline and online.

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ABSTRACT

Home automation systems can save a huge amount of energy by detecting home occupancy and sleep patterns to automatically control lights, HVAC, and water heating. However, the ability to achieve these benefits is limited by a lack of sensing technology that can reliably detect zone occupancy states. We present a new concept called *Walkway Sensing* based on the premise that motion sensors are more reliable in walkways than occupancy zones, such as hallways, foyers, and doorways, because people are always moving and always visible in walkways. We present a methodology for deploying motion sensors and a completely automated algorithm called *WalkSense* to infer zone occupancy states. WalkSense can operate in both offline (batch) and online (real-time) mode. We implement our system using two types of sensors and evaluate them on 350 days worth of data from 6 houses. Results indicate that WalkSense achieves 96% and 95% average accuracies in offline and online modes, respectively, which translates to over 47% and 30% of reduced energy wastage, and 71% and 30% of reduced comfort issues per day, in comparison to the conventional offline and online approaches.

1. Introduction

Heating and cooling are the largest sources of residential energy consumption, accounting for an estimated 48% of energy consumption in US homes.[1] However, many homes have multiple "zones", each of which requires a different level of heating and cooling. For example, many homes have a daytime zone (living room and kitchen) where the temperature should be comfortable and a nighttime zone (bedrooms and bathrooms) where the temperature can float. Another example includes two- or three-story homes where heating and cooling should be adjusted based on the floors that are occupied due to temperature stratification. To achieve this, some homes would put a central heating/cooling system into different *modes* based on zone occupancy state, while other homes would have independent thermal conditioning for each zone. Either way, substantial energy can be saved by using zone occupancy information to adjust the heating/cooling.

Studies have shown that energy usage can be reduced 20–30% by reducing heating and cooling when residents are asleep or away [1–3]. On a national scale, this would correspond to annual saving of 112 billion kW h in the US and would prevent the emission of approximately 1.2 billion tons of air pollutants [4]. However, studies have shown that occupants do not adjust their thermostats often enough to fully realize these savings [1,5]. To address this problem, the self-programmable [6] and smart thermostats [4] are designed to automatically learn occupants' schedules and turn the heating and cooling on or off on the user's behalf. However, the ability to achieve these benefits is limited by lack of sensing technologies that can reliably detect occupancy states [7–9].

The most common and intuitive approach to sense zone occupancy states is what we call *activity sensing*: install motion sensors in every zone, and the zones that contain activity are defined to be occupied. This approach is widely used for smart thermostats and home automation systems today [10,4] even though motion sensors are notoriously unreliable: they can fail to detect a person's presence if that person is out of view or sitting still (e.g. watching TV or sleep), which

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[1] http://www.eia.gov/consumption/residential/.

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creates ambiguity about which zones are occupied. Detecting occupancy in sleeping zones is especially difficult because people remain still for long periods of time while sleeping. In our survey of the occupancy sensing literature, we found no studies that could use motion sensors to reliably detect occupancy in a sleeping zone. Most studies exclude the nighttime hours from their evaluation altogether [11–14]. Other studies define sleep to be all periods of inactivity between certain hours, such as 10 pm–8 am [14,15], even though this approach produces errors every time a person sleeps during the day or goes out at night, both of which are common occurrences for many people, and especially for the nearly 15 million shift workers who work a permanent night shift or regularly rotate in and out of night shifts.[2]

In this paper, we present a new approach to reliably detect occupancy in the zones of a house using motion sensors. For the reasons described above, we do not rely on motion sensors to constantly detect activity in a zone. Instead, we primarily use motion sensors to detect occupancy in the walkways between zones, such as hallways, foyers, or doorways. We hypothesize that motion sensors will work more reliably in walkways than occupancy zones because people are always moving in walkways and do not sit still in them for long periods. In addition, walkways are small enough for the entire area to be within the view of a motion sensor. We therefore propose a new principle for the use of motion sensors that we call *Walkway Sensing*, and demonstrate that we can convert walkway sensing into a reliable form of occupancy sensing for zones. For concreteness, we explain and evaluate walkway sensing in the context of detecting the typical home's three main occupancy states: (1) *Active*: when at least one occupant presents in the daytime zone (e.g. living room and kitchen), (2) *Away*: when all occupants left the home, and (3) *Sleep*: when all occupants who are at home, are asleep. However, the underlying principles of walkway sensing will generalize to homes with other zone configurations.

To use walkway sensing to detect the active, sleep, and away states, we first *zone* the home into three distinct regions: the outside zone, the sleep zone, and the active zone. Second, we deploy motion sensors in the *walkways* between the three zones, such as the hallway, doorway, or foyer. Third, we deploy a motion sensor covering the main activities in the active zone. Based on this sensor placement, we design an occupancy detection algorithm called *WalkSense*, which comes in two variants. The *offline* variant operates in batch mode on historical data, labeling prior occupancy states with full knowledge of the data produced before and after the state occurred. In contrast, the *online* variant operates in real-time, labeling current occupancy states before subsequent data readings are observed. It is executed every time a person is detected in a walkway, which is on every potential transition event into or out of the sleep or away states.

The key challenge in the online WalkSense is learning the occupancy pattern changes using the training data. In general, supervised methods use historical data labeled manually for training, which is a time-consuming process. However, we require a dynamic model with continuous learning to identify changes in occupancy patterns of different zones. In this case, using the previous manual methods for annotation requires a constant user involvement. We address this challenge by designing an automatic labeling procedure which is built upon the offline WalkSense. The key insight is that the offline WalkSense uses all data before, after, and during an entire interval and can determine the state of the interval with very high certainty, which is suitable for annotation. Therefore, we iteratively derive the past sensor data and calculate their labels using the offline WalkSense.

We implement WalkSense using two types of sensors. The first implementation uses standard off-the-shelf motion sensors. Time stamp errors due to clock drifts is the main challenge, where we address that by designing a synchronization method. The second implementation called “Back-to-Back (B2B)” is a custom motion sensor package where a pair of PIR sensors are attached in two sides, one covering the walkway zone, and the other one covering the active zone. This design provides additional information about the walking direction into or out of the sleep/away zones. In addition, co-locating the sensors of the two zones provides the opportunity to use a common clock for both sensors through a single micro-controller to solve the issue of time synchronization.

We evaluate offline and online WalkSense with the two implementation designs on 6 homes resulting in 350 days worth of data. We deployed standard off-the-shelf motion sensors in 5 homes for 3–7 weeks in each home, using daily questionnaires to collect ground truth about the active, sleep, and away states in each home. We also used one public dataset with annotated ground truth that includes 26 weeks of data [16]. Results indicate that offline WalkSense can detect the home occupancy states with 96% accuracy and can reduce occupants comfort loss and energy waste by 71% and 47%, respectively, compared with the conventional activity sensing approaches [10]. The online WalkSense detects occupancy states with 95% average accuracy in real-time, and can reduce comfort issues and heating energy by 30% and 32%, respectively, compared with the conventional online occupancy inference algorithms [4]. In addition, analysis shows that 12% of detected sleeping instances are daytime napping and 11.7% of away periods happened at night, between 9 pm and 3 am, which highlights the robustness of the proposed method to irregular sleep and away patterns.

2. Background and related work

2.1. HVAC control systems

The standard goal of an HVAC control system is to keep temperature and air quality in a comfort range while minimizing energy usage. Programmable Thermostats or Rule-Based Control (RBC) systems are one of the most conventional control practice, which schedule different setpoint temperatures at different times throughout the day. However, the expected energy saving is premised on the ability of the occupants in defining the schedules that match the home occupancy patterns. This can be difficult specially for homes with multiple occupants with irregular occupancy patterns. Studies have shown that the risk of comfort loss causes people to reduce their use of setpoint schedules during unoccupied or sleeping periods [17]. Therefore, the setpoint temperature is usually above the safety limit of the house to reduce the risk of comfort loss, thus causing more energy consumption even when the home is vacant. A number of papers proposed the self-programming thermostat to fix this problem by automatically choosing the optimal setback schedules based on occupancy statistics [6,18]. However, this approach still generates static schedules and doesn't react to the dynamic occupancy changes throughout the day.

An alternative approach is to use Reactive Thermostats, which use different sensing modules to turn the HVAC on and off based on occupancy [19,20]. However, they are limited by the lack of a reliable occupancy sensing approach and an accurate occupancy detection algorithm. In addition, HVAC system and thermal properties of the home result in a certain time lag until the temperature setpoint is reached. Therefore, the inability of reactive thermostats to quickly respond to occupancy changes limits their potential energy saving. To address this problem, Smart Thermostats [11,4,21–23] and Model Predictive Control (MPC) systems [24–26] are proposed, which use the current and historical occupancy data to solve an optimal control problem for a finite prediction horizon, and automatically turning off and on the home's HVAC system. Studies have shown that this approach achieves a 28–35% energy saving on average [4]. All of these occupancy-based HVAC control systems require a reliable occupancy sensing system to correctly infer the occupancy data. This paper proposes a new occupancy sensing principle which is compatible with different HVAC control systems including programmable and smart thermostats. In

[2] http://www.cdc.gov/niosh/topics/workschedules/.