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Nonintrusive ultrasonic-based occupant identification for energy efficient smart building applications

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HIGHLIGHTS

- A novel method to identify occupants by sensing their shape and movement.
- This method is based on sensing height and width from ultrasonic ping sensors attached to the door.
- The system enables to identify up to 20 people with a 95% accuracy.
- The system does not require any training.

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ABSTRACT

The ability to non-intrusively identify people will enable smart buildings to customize the environment to meet occupants' comfort level while saving energy. Occupant identification can help in energy savings effort in a building because we can retrieve each occupant's temperature preference profile and choose the temperature that minimizes the total discomfort of a group in the building. To enable occupant identification in buildings, many methods used can be intrusive, such as using cameras or requiring the users to carry mobile gadgets or a smart phone. Non-intrusive techniques are gaining interest in smart building applications. In this paper, we present a non-intrusive ultrasonic based sensing technique to identify people by sensing their body shape and movement. The ultrasonic sensors are placed on the top and sides of doors to measure the height and width as the occupant walks through the instrumented doorway. Height and width and their related features can give a unique signature to occupants to identify them. In this study, the proposed system senses a stream of height and width data, recognizes the walking event when a person walks through the door, and extracts features that capture a person's movement as well as physical shape. These features are fed to a clustering algorithm that associates each occupant with a distinct cluster. The system was deployed for a total of three months. The results show that the proposed approach achieves 95% accuracy with 20 occupants suggesting the suitability of our approach in commercial building settings. In addition, the results show that using girth to distinguish between occupants is more successful than using height. We show that this system generalizes beyond our datasets and works for different populations of different physical distributions.

1. Introduction

Buildings energy consumption constitutes about 40% of the total energy consumed in the United States. There are efforts to develop buildings that are smart and energy efficient. Developing energy efficient buildings requires addressing challenges from different aspects including energy efficient building material, integrating renewable energies, and using more efficient Heating, Ventilation and Air Conditioning (HVAC) systems. The latter is a significant consumer of power in buildings, especially in warmer or colder areas. By having accurate estimates of occupancy or human activities inside buildings, one can develop smarter algorithms to better manage the HVAC yielding saved energy and increased occupants' comfort. Occupancy allows the first order optimization of HVAC use in a building. However, occupancy does not provide any information about the occupants' comfort levels. In fact, occupancy is mostly used to adjust the airflow, but the temperature of the air flowing to the various rooms is not a function of occupancy but rather constant and predefined by building managers. As a result, many occupants are uncomfortable in buildings because of the lack of customization and inability to tailor to the present occupant's thermal preferences. Thus, there is a case for identifying occupants in a building to customize the HVAC operation to meet the

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occupants preferences and avoiding the *too hot* or *too cold* scenarios, and hence energy waste.

Smart and energy efficient buildings need to tailor the climate to the occupants' preferences. This is important because not only can it make the buildings more comfortable but also save energy. In fact, studies have shown that we can achieve at least 30% energy savings by having an accurate estimate of occupancy Erickson et al. [1]. With accurate occupancy estimate, Erickson and Cerpa [2] show that we can adjust the HVAC airflow by feeding the occupied areas with just enough air given the number of occupants. However, even though we can achieve optimum airflow thus saving energy, there is no way for the occupants to provide feedback about their comfort given the set temperature. This leads to increased discomfort and missed energy saving opportunities because by having the occupants' comfort profile, we can set the temperature to accommodate as much people as possible. Current HVAC systems have predefined temperature settings low enough to accommodate every occupant's preference in the case of cooling and vice versa for heating. However, there are different temperature setting strategies that can be performed such as choosing the median temperature, mean, or various voting-based strategies as shown in Zhang et al. [3] or by taking into account thermal occupant comfort constraints as shown by Ghahramani et al. [4]. Most importantly, having a way to retrieve the occupants' temperature preference is crucial to making the buildings more comfortable, more adaptable and more energy efficient than by simply relying on occupancy sensing.

In this paper, we propose a non-intrusive ultrasonic based indoor occupant identification system that can be implemented in doorways that scale to accurately identifying 20 users which can be used in commercial applications such as buildings and nursing homes. The sensing technique measures the occupant's shape and movement which are used by a clustering algorithm to identify people. The proposed solution mounts three ultrasonic ping sensors at the top and the side of the door frame to measure occupants' height and girth. The sensors at the side of the door are used to compute the width of the person passing through it. Using the height and width time series, the system extracts a set of features to infer the occupant's body shape and movement. We identity occupants by clustering data from these features to uniquely characterize occupants. This makes our solution easy to use since it doesn't require to train the model because it's based on clustering. This solution can easily be integrated into doors and is cost effective since it uses off-the-shelf ultrasonic sensors.

Given that we rely on height and width which are weak biometrics, the system is subject to uncertainty as some people may have similar height and width measures. This paper studies the extent to which such similarities will affect the system's performance. Our findings show that clustering with the body shape and time spent walking through the door (thus movement) enables us to accurately identify people. The results show that indeed these parameters are key to differentiating between people thus achieve 95% accuracy for 20 people and 75% for 50 people.

We introduce the system design which includes sensing methods, data filtering techniques to minimize noise from the measurements, and clustering algorithms to identify occupants. We conducted two experiments: a room-scale experiment that lasted one month long involving 20 people in a classroom environment at the University of Houston and a building-scale experiment involving five door frames for a period of two months with over 170 participants.

1.1. Contributions

The contributions of this paper are:

- We propose and implement a system that identifies occupants using height and width measured using ultrasonic sensors mounted in doors. The system extract a set of useful features which are used by a clustering algorithm to identify people.
- We Investigate the impact of the computed features on the accuracy of the system. In particular, our results show that gait contributes more significantly to identification than height.
- We compare the accuracy of different combinations of features in identifying occupants. The results show that clustering with girth and time provide more accurate results than height and time.
- We investigate how the method scales for larger populations of up to 50 people.
- We investigate how would the system perform on different populations of different physical characteristics. We perform that by drawing samples that match a physical characteristics and evaluating the performance of our model on it.

Relative to our preliminary work in Khalil et al. [5], we deployed a new large scale testbed composed of five door frames for a period of two months with over 170 people participants. This was important to evaluate how consistent is the system performance when conducted with more and different participants and in different locations involving more door frames. We also studied the extent to which such a system would scale to different populations with different characteristics and how would the performance change as we scale the population size. We also explored the use of Spectral clustering on how it performs compared to DBSCAN. We evaluated the walking event performance. Our research demonstrates that it is possible to identify occupant with 95% accuracy for 20 people and 75% for 50 people.

2. Related work

2.1. HVAC control

HVAC is one of the main power consumers in buildings in the US. In fact, it consumes 50% of building energy consumption and 20% of the total energy consumption Pérez-Lombard et al. [6]. Thus, numerous research has been done to make these systems more energy efficient. A few researchers have explored the possibility of augmenting the HVAC control with occupancy information for the purpose of energy saving Conte et al. [7], Färber et al. [8], Erickson and Cerpa [2], Erickson et al. [1]. Also, Brandemuehl and Braun [9] showed that energy could be saved by adjusting ventilation to maximum occupancy, and Erickson et al. [10] showed that the majority of current HVAC systems assume maximum occupancy during normal hours and turn it off during the evening which is a source of inefficiency because rooms are not always at maximum occupancy. Therefore, an accurate occupancy estimate could save energy by adjusting the ventilation to the estimated occupancy rather than maximum occupancy.

However, having an accurate estimate of occupancy is not enough to save energy. In fact, Hoyt et al. [11] has shown that by increasing the set point temperature by 1 °C, we can save 7–15% energy consumed by the HVAC in the summer in three cities namely San Francisco, Miami and Phoenix. These savings are achievable because a large fraction of users feel that the temperature set points in their building is too extreme. In fact, in a study at the University of Southern California, Jazizadeh et al. [12] showed that 60% of the users felt cool to cold inside the building during the summers showing the potential to raise the temperature which would increase the users' comfort and save energy. So one can make the occupants more comfortable as well as save energy having users comfort preference.

2.2. Setting HVAC temperature

Having an estimate of occupancy is crucial to achieve proper ventilation, but understanding the thermal preference of users would help save even further by taking into consideration the occupants' preferences. In fact, Karjalainen and Koistinen [13] discuss that the lack of control as well as individual control in buildings increase occupants' discomfort in offices because the systems are planned without an understanding of the users which change over time. Erickson and Cerpa