A Non-Invasive Sensing System for Decoding Occupancy Behaviors Affecting Building Energy Performance

Triana S. Carmenate[1], Diana Leante[2], Sebastian A. Zanlongo[3], Leonardo Bobadilla[4], Ali Mostafavi[5]

[1]Graduate Research Assistant, School of Computing and Information Sciences, College of Engineering and Computing, Florida International University
[2]Undergraduate Research Assistant, School of Computing and Information Sciences, College of Engineering and Computing, Florida International University
[3]Doctoral Research Assistant, School of Computing and Information Sciences, College of Engineering and Computing, Florida International University
[4]Assistant Professor, School of Computing and Information Sciences, College of Engineering and Computing, Florida International University
[5]Assistant Professor, OHL School of Construction, College of Engineering and Computing, Florida International University
E-mail: {[1]tcarm002, [2]delan001, [3]szan001, [5]almostaf}@fiu.edu, [4]bobadilla@cs.fiu.edu

Abstract

Occupancy behaviors have been recognized as a major source of uncertainty in assessment of energy performance in buildings. The limitations in collecting information regarding occupancy behaviors have hindered the ability to fully decode the emergent occupant behaviors affecting the energy performance of buildings. In this paper, we demonstrate our preliminary results related to a novel system for non-invasive tracking of occupancy behaviors. Our analysis will consist of the deployment of a system, consisting of a non-invasive sensor network, to capture the movements of occupants and their behaviors within a residence while recording the information related to the lighting and indoor temperature, of the location. Utilizing small Infrared sensors, the building's occupant's movements are detected and the occupancy levels are recorded without having to uniquely identify individuals. The proposed system is demonstrated in a case study of a residential home. Data collected from the case study shows the capability of the proposed system in capturing occupancy behaviors using minimal information in a non-invasive and inexpensive fashion. The methodology used can serve as a basis for detecting behaviors that lead to energy waste in buildings. The system implemented has the ability to capture information required to integrate building performance and occupant behaviors towards the realization of smart buildings.

Introduction

According to the United States Green Building Council, buildings account for 39% of CO_2 emissions in the U.S. and consume 70% of electricity load in the U.S. Despite efforts towards evaluating energy performance in buildings, there is a significant discrepancy in the actual energy performance of buildings (compared to designed energy performance) mainly due to occupant's behaviors [Hong, 2014]. Different dimensions of occupant's behaviors (such as knowledge, environmental cognition, and occupancy) affect the energy performance of buildings. This paper focuses mainly on the impacts of occupancy on the energy performance of buildings. For the purpose of this study, we define occupancy as the presence, movement, and interaction of occupants with building units and appliances. Our working hypothesis is that there are certain measures that can be used for understanding uncertainties in building energy performance based on capturing human-building interactions. Examples of the impacts of occupancy on building energy performance are as follows:

I. Lighting-related energy waste: The availability of a certain level of lighting in a building unit should be contingent on the presence of occupants. Providing a certain level of lighting while occupants are not present could lead to waste of electricity.

II. Plug-load energy waste: The use of certain plug-loads (such as TV) should be contingent on the presence of occupants. Using plug-loads while occupants are not present could lead to waste of electricity.

III. Heating/cooling-related energy waste: The temperature of a unit should be consistent with the comfort level of occupants as well as the number of occupants in a building unit. Providing a level of heating/cooling in excess of the level required to maintain the comfortable temperature for a certain number of occupants could lead to waste of electricity.

Hence, decoding occupancy behaviors is critical for better understanding of the uncertainty in building energy performance. Recent studies such as [Klein et al., 2012] and [Hong, 2014] have investigated the importance of capturing and evaluating occupants behaviors in improving the energy efficiency of buildings. While the majority of the existing studies, such as [Masoso and Grobler, 2010], in this area focus on improving occupants knowledge (based on responsive strategies and adaptive communication), another potential solution for eliminating these energy inefficiencies is to effectively track the location and distribution of occupants within different units in a building to proactively investigate circumstances when waste of energy happens (see Figure 1. In this paper, we focus on our first step toward decoding occupancy behaviors and their impact on building energy waste. We propose a non-invasive sensing methodology to investigate two main issues in this study: (i) presence of occupants in a building unit; and (ii) distribution of occupants across building units. The proposed methodology will facilitate tracking of occupants in buildings to investigate effective strategies for reducing electricity waste. The following sections explain the theoretical underpinnings of the proposed sensing methods followed by a preliminary experimental setting in a residential house.

		Data from Sensors					
		Lighting Data			Plug Load Data		Temperature
		On	Off	Illuminance (lux)	On	Off	°C
Occupant Presence	Yes	OK	Discomfort	Level of lighting greater than comfort Level, then energy waste	OK	OK	Level of temperature greater than comfort Level, then energy waste
	No	Waste	OK	Waste	Waste	OK	OK

Figure 1. Example of detecting energy waste using occupancy and sensor information.

Methodology

To detect occupancy behaviors we propose a minimalist approach that consists of collecting data using non-invasive techniques. A sensor network comprised of paired Infrared directional beams ([Bobadilla et al., 2011], [Tovar et al., 2014]), ambient light sensors, a thermostat, and plug load detectors will provide the information needed to accurately estimate energy expenditure and waste in a given environment. Occupancy information can be represented as $O = [0, 1]$ where 1 represents that there are occupants in a given region and 0 means the region is empty. This information will be obtained from a crossing beam placed at doorways and entry points for a region. Light information can be obtained using ambient light sensors and will be represented as a vector as $\mathcal{L} = \{l^1, l^2, \cdots, l^n\}$, where n represents the number of lights in a region. Plug load information is also represented as a vector, $\mathcal{P} = \{p^1, p^2, \cdots, p^n\}$, where n represents the number of plug loads in a region. This information combined will give us a *state space* at any given point in time for a specified region. This state space can be used to compare data gathered from an environment with the actual kilowatt usage reports from the electric company to determine what percentage of energy was wasted based on occupancy.

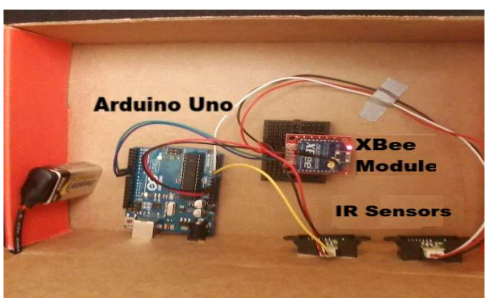
Experimental Setup

In this section, we demonstrate an inexpensive hardware implementation using low-cost Infrared (IR) sensor beams, a temperature sensor and a wireless communication system. We conducted several experiments showing the efficacy of this system. For the purposes of this preliminary experiment we did not incorporate ambient light and plug load information sensors.

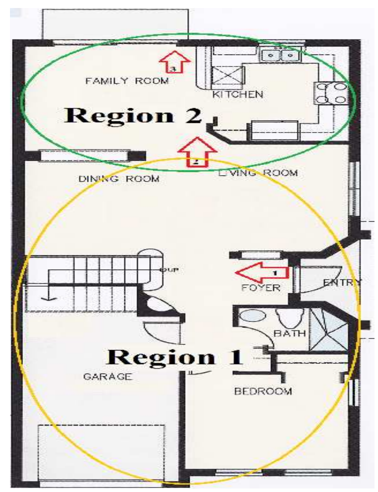
Hardware Setup. The sensor beams were formed using pairs of IR emitter-sensors to create sets of parallel directed beams. Unlike previous experiments such as [Zappi et al., 2010], which use a single beam to detect a crossing, our double beam implementation allows for tracking the direction of an object depending on which beam is first occluded.

Each node in Figure 2a handles the processing of this data through an Arduino Uno single-board micro-controller with the results being transmitted through an XBee wireless Radio-Frequency (RF) module. Figure 2b shows the placement of the nodes in the environment. The XBee modules were connected using the DigiMesh networking protocol, providing self-healing and automatically expandable network, allowing for simple and quick deployment.

The hardware and design of the node modules were based on the need for an easy deployment in a commercial as well as residential setting. By using the equipment mentioned above, nodes do not require network hookups, and the network itself requires little to no configuration or pre-planning. They can be powered using batteries or a power hookup. This allows sensor operators to simply focus on the optimal tracking locations, rather than being constrained by other concerns.



(a) Crossing node hardware setup.



(b) Floorplan with node placement depicted by arrows.

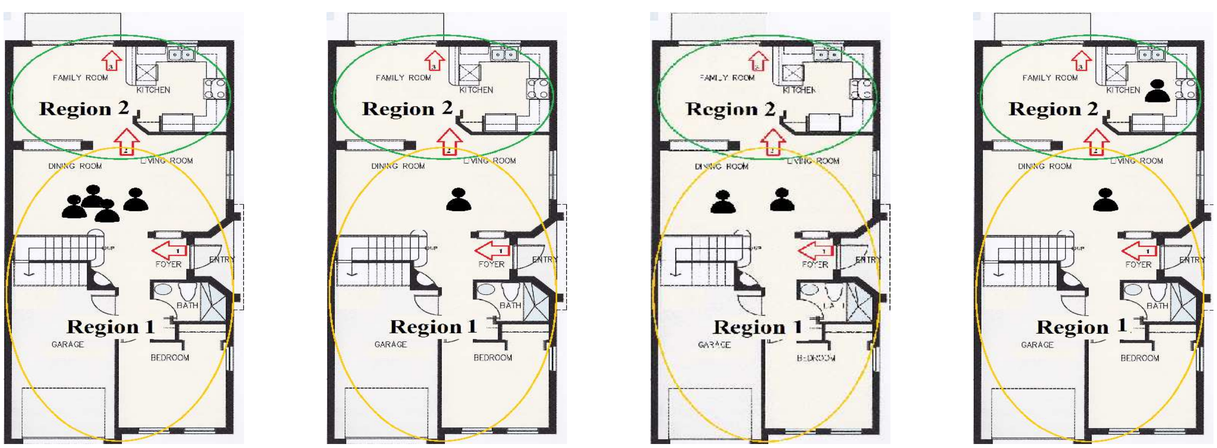
Figure 2. Hardware for a crossing node and placement of nodes in a household.

The materials were chosen for their small form-factor, low-cost, and ease of use that will enable large-scale deployment when compared to expensive camera systems [Agarwal et al., 2010]. The total cost for a single node is \$104, including the cost of cables, batteries, and breadboard. The environment for our experiment was divided into 2 regions utilizing 3 nodes in order to capture occupancy information. One node was placed between the two regions and the other two nodes were placed at the front and back doors of the house. The total cost for this setup was \$317.95, including the cost of an inexpensive temperature sensor. In order to fully capture the occupancy information for this household, 5 more nodes would be needed to segregate the environment into additional regions. The total cost then would be \$837.95.

Hardware Deployment. Preliminary testing consisted of occluding both single and parallel beams, and verifying that the direction of occlusion was correctly determined. Following this, a basic setup of three nodes was deployed in a residential environment to track occupant movements. Because of the simple design of the nodes, deployment could be easily scaled for an office environment.

Experimental testing showed that the software and hardware are capable of repeatedly detecting crossings. Three nodes were deployed in the house with each node monitoring an entryway to another area, or *region*, of the house (see floorplan in Figure 3). Although the direction of crossings was shown to have occasional errors when in sunlight, these errors are significantly reduced when indoors, the primary environment of this deployment.

One of the nodes (the arrow labeled *1* in Figure 3) was placed by the front door of the house to detect people entering or leaving the house and *region 1*. Another node (arrow *2*) was placed at an open cross way between the living room and the dining room/kitchen area, *region 2*, to detect people entering region 2, and leaving region 1. The final node (arrow *3*) was placed near the back door, to detect people leaving region 2. Future setups could break an environment into more regions, allowing us to have a finer degree of occupancy data. Figure 4a shows the first node's placement in region 1 and Figures 4b and 4c show a resident crossing though different regions.

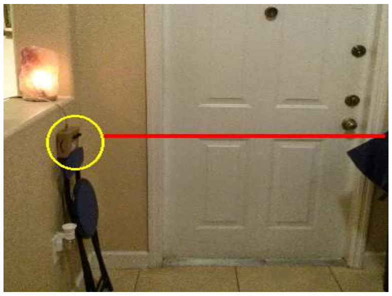


(a) *t=8:00 PM.* **(b)** *t=8:11 PM.* **(c)** *t=11:00 PM.* **(d)** *t=11:10 PM.*

Figure 3. Floorplan of residence with occupancy at different times, *t*. The directional arrows indicate node placement.

Results

Data was collected that measured the occupancy of the different regions of the house throughout a 24-hour period from 6:40 PM to 5:52 PM the next day (Figure 5). When compared against energy usage data collected from the electric company, Figure 6, one can see that there is a general correlation between occupancy of the house and energy



(a) Node placed at house entryway.

(b) Resident crossing Node 1 and leaving home/Region 1.

(c) Resident exiting Region 2 and entering Region 1.

Figure 4. Node placement and crossing detection. Nodes are circled and the beam is indicated by a line. The crossing occupant breaks the beam emitted by the sensor.

expenditure. For example, from around 8 PM to 10 PM there was only one person in the household. This time period had a decrease in energy consumption from about 1.65 kilowatts per hour (kWh) to .8 kWh. More occupants entered the house around 10 PM and energy consumption increased to 1.65 kWh. Another clear correlation between occupancy and energy consumption is denoted by the dashed-line boxes in Figures 5 and 6 where the residence was empty from around 9:30 AM to around 4:30 PM. Energy consumption decreases at this time period and increases once a resident arrives in the afternoon.

Ambient temperature was also recorded on one of the nodes via an inexpensive temperature sensor(TMP102 from SparkFun). Combining the information from temperature sensor and occupancy data, we can determine instances of energy waste. For example, between 9:30 AM and 4:30 PM, there were no occupants in the household, however, the air conditioning was on and causing energy waste.

Conclusion

Understanding occupancy behaviors is a critical step toward better understanding of occupant-building-appliance interactions and reducing energy waste in buildings. In addition, accurate and real time tracking of occupants in buildings could provide insights for smart building energy management. This can then be used to modify building plans and appliance placement. Locations with low occupancy can best benefit from energy-saving measures that favor cutting power, whereas high-occupancy locations can be better served by measures that improve efficiency for always-on appliances. The system would help existing buildings by identifying energy waste so that building owners could implement measures to reduce unnecessary energy consumption. We proposed a non-invasive and inexpensive sensor system for tracking occupancy in buildings that will preserve the privacy of building occupants while helping to capture instances of energy waste.

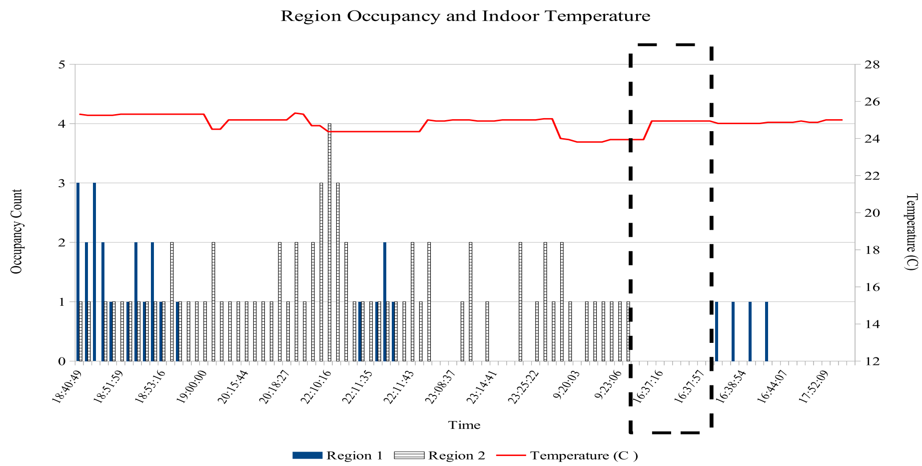


Figure 5. Residence occupancy from 6:40 PM to 5:52 PM the next day. Dashed-line box indicates a period of time when home was empty and energy was still being consumed, as denoted in Figure 6.

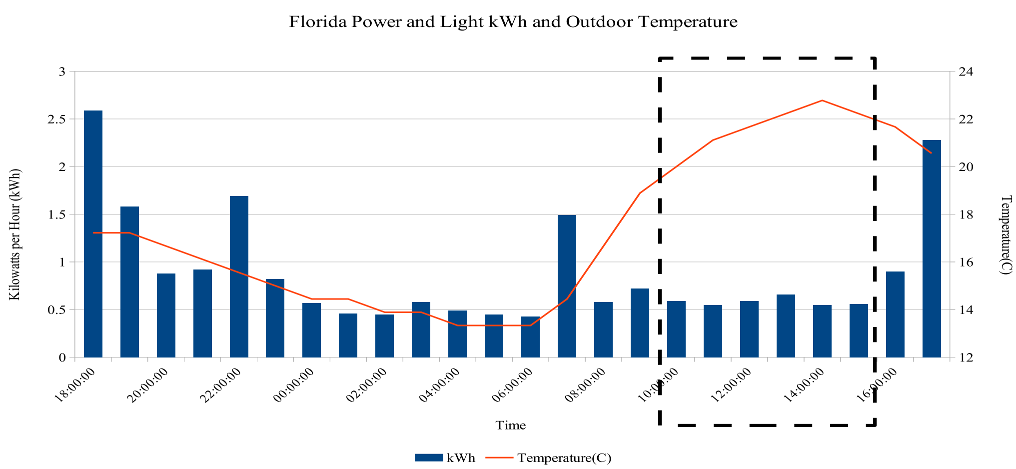


Figure 6. Energy usage from electric company. Bars indicate kWh consumed, line represents outdoor temperature. Dashed-line box corresponds to the box in Figure 5.

Future Work and Suggested Improvements. The sensor system presented in this paper is one component of our envisioned system for capturing occupant-building-appliance interactions. One of the limitations observed in our system was the IR sensors utilized in our nodes. They were accurate in detecting when a crossing occurred, but they were not completely accurate in detecting how many people crossed a node and in which direction. One possibility that might have caused this is the cone shaped infrared beam emitted by the sensor. We plan on refining this beam into a narrow line, as done in other experiments such as [Blonchek et al., 2013], to obtain more accurate crossing data.

Another viable option would be replacing the Infrared Sensors beams with Ultrasonic beams. Ultrasonic beams are not affected by sunlight, and can therefore be used outdoors whereas our existing implementation cannot.

The experiment presented in this study did not include lighting and plug-load sensors. Future experiments will include data collected from plug load's throughout an environment as well as lighting data from ambient light sensors. We also plan on asking residents their temperature preferences to obtain an average temperature that residents are comfortable with. This information, combined with region occupancy data, will facilitate detecting energy waste at the interface of occupant-building-energy interactions and could provide insights for improving the energy performance of buildings.

References

Yuvraj Agarwal, Bharathan Balaji, Rajesh Gupta, Jacob Lyles, Michael Wei, and Thomas Weng. Occupancy-driven energy management for smart building automation. In *Proceedings of the 2nd ACM Workshop on Embedded Sensing Systems for Energy-Efficiency in Building*, pages 1–6. ACM, 2010.

Jonathon Blonchek, Shiv Sinha, Anish Simhal, and Vinay Dandeka. Rice nook sensors: Occupancy sensing in an academic environment. *The Spectra*, 4:21–26, May 2013.

Leonardo Bobadilla, Oscar Sanchez, Justin Czarnowski, and Steven M LaValle. Minimalist multiple target tracking using directional sensor beams. In *Intelligent Robots and Systems (IROS), 2011 IEEE/RSJ International Conference on*, pages 3101–3107. IEEE, 2011.

Tianzhen Hong. Occupant behavior: impact on energy use of private offices. In *ASim 2012-1st Asia conference of International Building Performance Simulation Association., Shanghai, China, 11/25/12-11/27/12*, 2014.

Laura Klein, Jun-young Kwak, Geoffrey Kavulya, Farrokh Jazizadeh, Burcin Becerik-Gerber, Pradeep Varakantham, and Milind Tambe. Coordinating occupant behavior for building energy and comfort management using multi-agent systems. *Automation in Construction*, 22:525–536, 2012.

OT Masoso and LJ Grobler. The dark side of occupants behaviour on building energy use. *Energy and Buildings*, 42(2):173–177, 2010.

Benjamin Tovar, Fred Cohen, Leonardo Bobadilla, Justin Czarnowski, and Steven M Lavalle. Combinatorial filters: Sensor beams, obstacles, and possible paths. *ACM Transactions on Sensor Networks (TOSN)*, 10(3):47, 2014.

Piero Zappi, Elisabetta Farella, and Luca Benini. Tracking motion direction and distance with pyroelectric ir sensors. *Sensors Journal, IEEE*, 10(9):1486–1494, 2010.