

Developing a robust system for occupancy detection in the household

Ash Tyndall

*This report is submitted as partial fulfilment
of the requirements for the Honours Programme of the
School of Computer Science and Software Engineering,
The University of Western Australia,
2014*

Abstract

This is the abstract.

Keywords: keyword, keyword

CR Categories: category, category

Acknowledgements

These are the acknowledgements.

Contents

Abstract	ii
Acknowledgements	iii
1 Introduction	1
2 Literature Review	2
2.1 Sensors	3
2.1.1 Intrinsic traits	4
2.1.2 Extrinsic traits	6
2.2 Thermal sensors	7
2.3 Architecture	8
3 Methods	9
4 Results	10
5 Discussion and Conclusion	11
A Original Honours Proposal	12
A.1 Background	12
A.2 Aim	13
A.3 Method	14
A.3.1 Hardware	14
A.3.2 Classification	14
A.3.3 Robustness / API	15
A.4 Timeline	15
A.5 Software and Hardware Requirements	16

A.6 Proposal References	17
-----------------------------------	----

List of Tables

2.1	Comparison of different sensors and project requirements	7
-----	--	---

List of Figures

CHAPTER 1

Introduction

CHAPTER 2

Literature Review

The proportion of elderly and mobility-impaired people is predicted to grow dramatically over the next century, leaving a large proportion of the population unable to care for themselves, and consequently less people able care for these groups. [6] With this issue looming, investments are being made into a variety of technologies that can provide the support these groups need to live independent of human assistance.

With recent advancements in low cost embedded computing, such as the Arduino [1] and Raspberry Pi, [2] the ability to provide a set of interconnected sensors, actuators and interfaces to enable a low-cost ‘smart home for the disabled’ is becoming increasingly achievable.

Sensing techniques to determine occupancy, the detection of the presence and number of people in an area, are of particular use to the elderly and disabled. Detection can be used to inform various devices that change state depending on the user’s location, including the better regulation energy hungry devices to help reduce financial burden. Household climate control, which in some regions of Australia accounts for up to 40% of energy usage [3] is one particular area in which occupancy detection can reduce costs, as efficiency can be increased dramatically with annual energy savings of up to 25% found in some cases. [5]

While many of the above solutions achieve excellent accuracies, in many cases they suffer from problems of installation logistics, difficult assembly, assumptions on user’s technology ownership and component cost. In a smart home for the disabled, accuracy is important, but accessibility is paramount.

The goal of this research project is to devise an occupancy detection system that forms part of a larger ‘smart home for the disabled’ that meets the following accessibility criteria;

- *Low Cost*: The set of components required should aim to minimise cost, as these devices are intended to be deployed in situations where the serviced user may be financially restricted.

- *Non-Invasive*: The sensors used in the system should gather as little information as necessary to achieve the detection goal; there are privacy concerns with the use of high-definition sensors.
- *Energy Efficient*: The system may be placed in a location where there is no access to mains power (i.e. roof), and the retrofitting of appropriate power can be difficult; the ability to survive for long periods on only battery power is advantageous.
- *Reliable*: The system should be able to operate without user intervention or frequent maintenance, and should be able to perform its occupancy detection goal with a high degree of accuracy.

To create a picture of what options there are in this sensing area, a literature review of the available sensor types and wireless sensor architectures is needed. From this list, proposed solutions will be compared against the aforementioned accessibility criteria to determine their suitability.

2.1 Sensors

To achieve the accessibility criteria, a wide variety of sensing approaches must be considered. It can be difficult to approach the board variety of sensor types in the field, so a structure must be developed through which to evaluate them. [14] proposes a 5-element human-sensing taxonomy that is very useful in considering the broad requirements of sensors for this research.

The taxonomic elements are;

1. *Presence*: Is there anyone present in the sensed area?
2. *Count*: How many people are there in the sensed area?
3. *Location*: Where are the people in the sensed area?
4. *Track*: Where do the people move in the sensed area? (local identification)
5. *Identity*: Who are the people in the sensed area? (global identification)

These elements are particularly useful when it comes to comparing the different qualities of sensors, and to determine which sensors are useful for our particular purpose. At a fundamental level, this research project requires a sensor system that provides both Presence and Count information. To assist with

the reduction of privacy concerns, excluding systems that permit Identity will generally result in a less invasive system also. The presence of Location or Track are irrelevant to our project’s goals, but overall, minimising these elements should in most cases help to maximise the energy efficiency of the system also.

[14] also proposes a measurable human trait taxonomy, which we use in this literature review as a structure through which we describe different sensor types.

2.1.1 Intrinsic traits

The first set of sensors discussed are sensors detecting intrinsic traits. Intrinsic traits are those which can be sensed that are a direct property of being human. Intrinsic traits are particularly useful, as in many situations they are guaranteed to be present if a human is present. However, they do have varying degrees of detectability and differentiation between people. Two main subcategories of these sensor types are static and dynamic traits.

Static traits are physiologically derived, and are present with most (alive) humans.

One key static trait that can be used for human sensing is that of thermal emissions. All humans emit a large amount of thermal radiation in both resting and active states. The heat signatures of these emissions could potentially be measured with some apparatus, counted, and used to provide Presence and Count information to a sensor system, without providing Identity information. Once such paper that proposes this is [5], which uses a type of thermal sensor known as an infrared array sensor. This sensor is much like a camera, in that it has a field of view which is divided into an 8×8 grid of detected temperatures. This sensor is mounted on an embedded device on the roof, along with a Passive Infrared Sensor (PIR) , and uses a variety of classification algorithms to detect human heat signatures within the raw thermal and motion data it collects. Such a system achieves Root Mean Squared Error ≈ 0.35 persons. There are few drawbacks with this approach.

Another static trait is that of CO₂ emissions, which, like thermal emissions, are present in both resting and active states. By measuring the buildup of CO₂ within a given area, one can use a variety of mathematical models of human CO₂ production to determine how many people there are likely in a space to have that amount of CO₂ produced. This was trialled as part of a sensor fusion in [9], within the context of an office environment, achieving a $\approx 94\%$ accuracy. Such a sensing system could provide both the Presence and Count information, and exclude the Identity information as required. However, a CO₂ based detection mechanism has serious drawbacks, discussed in [8]; the CO₂ feedback mechanism

is very slow in nature, taking hours of continuous occupancy to correctly identify the presence of people. In a home environment, people are more likely to be moving between rooms than an office, so the system may have a more difficult time detecting in that situation. Similarly, such systems can be interfered with by other elements that control the CO₂ buildup in a space, like air conditioners, open windows, etc. This is also much more of a concern in a home environment compared to the studied office space, as the average home can have numerous such confounding factors.

The final static trait discussed is actual visual identification, achieved through the use of video or still-image cameras and advanced image processing algorithms. Video can be used in occupancy detection in several different ways, achieving different levels of accuracy and requiring different configurations. The first use of video, discussed in [7] is the use of video as a “optical turnstile”; the video system detects people and the direction they are moving in at each entrance and exit to an area, and uses that information to extrapolate the number of people within the turnstiled area; this system has up to a 94% accuracy. However, the main issue with such a system applied to a home environment is the system assumes that there will be wide enough “turnstile areas”, corridors of a fairly large area that connect different sections of a building, to use as detection zones. While such corridors exist in office environments, they are less likely to exist in home ones.

The second use of video is a ceiling-based video system [13], it uses advanced image processing algorithms to count the number of people in the captured area. This system achieves a specificity of $TP/(TP + FP) \approx 97\%$ and a sensitivity $TP/(TP + FN) \approx 96\%$ (TP = true positives, FP = false positives, FN = false negatives). Such a system could be successfully applied to the home environment, as both it and the “optical turnstile” model provide Presence and Count information. However, these systems also allow Identity to be determined, and are thus very invasive. Such invasive systems cannot be used due to privacy concerns.

Dynamic traits are usually products of human activity, and thus can generally only be detected when a human is physically active or in motion.

The first discussed dynamic trait based system is [10], an ultrasonic system that uses clusters of such sensors above doorframes to detect the height and direction of people travelling between rooms. This acts as a turnstile based system, much like [7], but augments this with an understanding of the model of the building to error correct for invalid and impossible movements brought about from sensing errors. This system provides an overall room-level tracking accuracy of 90%, however to achieve this accuracy, individuals are intended to be tracked using their heights, which is a privacy consideration. The system can also suffer

from problems with error propagation, as there are possibilities of “phantom” people entering a room due to sensing errors.

The second dynamic trait system is based upon a PIR connected to a transmitter of some description. A solely PIR based system is used within [9], with the motion of the sensor being averaged over several different time intervals, and fed into a decision tree classifier. This PIR system alone produced a $\approx 98\%$ accuracy. However, such a system, due to only motion detection capabilities, can only provide Presence information, and is unable to provide Count information.

2.1.2 Extrinsic traits

The second set of sensors discussed are sensors detecting extrinsic traits. Extrinsic traits are those which are actually other environmental changes that are caused by or correlated with human presence. These traits generally present a less accurate picture, or require the sensed humans to be in some way “tagged”, but they are generally also easier to sense in of themselves.

The sensors in this category have been divided into two subcategories for our purposes that are not discussed in [14]. The first of these categories is instrumented approaches; these require that detectable humans carry with them some device that is detected as a proxy for the human themselves.

The most obvious of these approaches is a specially designed device. [12] uses RFID tags placed on building occupant’s persons and a set of transmitters to triangulate the tags and place them within different thermal zones for the use of the HVAC system. For stationary occupants, there was a detection accuracy of $\approx 88\%$, and for occupants who were mobile, the accuracy was $\approx 62\%$. Such a system could be repurposed for the home, however, these systems raise issues in a home environment as it requires individuals to be constantly carrying their sensors, which is not the case in such an environment. Additionally, the accuracy for this system is not necessarily high enough for a home environment, where much smaller rooms are used.

To make extrinsic detection more reliable, [11] leverages a device people are likely to carry around; wifi enabled smart phones. They propose the *homeset* algorithm, which uses the phones to scan the visible wifi networks, and from that information estimate if the users are at home or out and about. This solution does not provide the fine-grained Presence data that we need, as it is only able to triangulate the phone’s position very roughly with the wireless network detection information.

[4] also leverages smart phones to determine occupancy, but in a more broad

	Requires		Excludes	Irrelevant	
	Presence	Count	Identity	Location	Track
<u>Intrinsic</u>					
<i>Static</i>					
Thermal	✓	✓	✓	✓	
CO ₂	✓	✓	✓		
Video	✓	✓	✗	✓	✓
<i>Dynamic</i>					
Ultrasonic	✓	✓	✗		✓
PIR	✓	✗	✓		
<u>Extrinsic</u>					
<i>Instrumented</i>					
RFID	✓*	✓	✓	✓	
Smart phone	✓*	—#	✗	✓	
GPS	✓*	✗	✓	✓	
<i>Correlative</i>					
Electricity	✓	✗	✓		
Network	✓	✗	✓		

* Doesn't provide data at required level of accuracy for home use.

Implementations vary in success for this characteristic.

Table 2.1: Comparison of different sensors and project requirements

enterprise environment: Wireless logs are analysed to determine which access points in a building a given user is connected to. If this access point falls within the radio range of their designated “personal space”, they are considered to be occupying that personal space. This technique cannot be applied to a home environment, as there are usually not multiple wireless hotspots.

2.2 Thermal sensors

A primary static/dynamic sensor fusion system in this field is the Thermosense system, [5] a PIR and Infrared Array Sensor (IAR) ¹ used to subdivide an area into an 8×8 grid of sections from which temperatures can be derived. This sensor system is attached to the roof on a small embedded controller which is responsible for collecting the data and transmitting it back to a larger computer via low powered wireless protocols.

¹Phillips GridEYE; approx \$30

The Thermosense system develops a thermal background map of the room using an Exponential Weighted Moving Average (EMWA) over a 15 minute time window (if no motion is detected). If the room remains occupied for a long period, a more complex scaling algorithm is used which considers the coldest points in the room empty, and averages them against the new background, then performs EMWA with a lower weighting.

This background map is used as a baseline to calculate standard deviations of each grid area, which are then used to determine several characteristics to be used as feature vectors for a variety of classification approaches. The determination of the feature vectors was subject to experimentation, with the differences at each grid element too susceptible to individual room conditions to be used as feature vectors. Instead, a set of three different features was designed; the number of temperature anomalies in the space, the number of groups of temperature anomalies, and the size of the largest anomaly in the space. These feature vectors were compared against three classification approaches; K-Nearest Neighbors, Linear Regression and an a feed-forward Artificial Neural Network of one hidden layer and 5 perceptions. All three classifiers achieved a Root Mean Squared Error (RMSE) within 0.38 ± 0.04 . This final classification is subject to a final averaging process over a 4 minute window to remove the presence of independent errors from the raw classification data.

Using the Melexis MLX90620 (*Melexis*)

2.3 Architecture

CHAPTER 3

Methods

CHAPTER 4

Results

CHAPTER 5

Discussion and Conclusion

APPENDIX A

Original Honours Proposal

Title: Developing a robust system for occupancy detection in the household
Author: Ash Tyndall
Supervisor: Professor Rachel Cardell-Oliver
Degree: BCompSci (24 point project)
Date: August 15, 2014

A.1 Background

The proportion of elderly and mobility-impaired people is predicted to grow dramatically over the next century, leaving a large proportion of the population unable to care for themselves, and consequently less people able care for these groups. [6] With this issue looming, investments are being made into a variety of technologies that can provide the support these groups need to live independent of human assistance.

With recent advancements in low cost embedded computing, such as the Arduino [1] and Raspberry Pi, [2] the ability to provide a set of interconnected sensors, actuators and interfaces to enable a low-cost ‘smart home for the disabled’ is becoming increasingly achievable.

Sensing techniques to determine occupancy, the detection of the presence and number of people in an area, are of particular use to the elderly and disabled. Detection can be used to inform various devices that change state depending on the user’s location, including the better regulation energy hungry devices to help reduce financial burden. Household climate control, which in some regions of Australia accounts for up to 40% of energy usage [3] is one particular area

in which occupancy detection can reduce costs, as efficiency can be increased dramatically with annual energy savings of up to 25% found in some cases. [8]

Significant research has been performed into the occupancy field, with a focus on improving the energy efficiency of both office buildings and households. This is achieved through a variety of sensing means, including thermal arrays, [5] ultrasonic sensors, [11] smart phone tracking, [12][4] electricity consumption, [13] network traffic analysis, [15] sound, [10] CO₂, [10] passive infrared, [10] video cameras, [7] and various fusions of the above. [16][15]

A.2 Aim

While many of the above solutions achieve excellent accuracies, in many cases they suffer from problems of installation logistics, difficult assembly, assumptions on user's technology ownership and component cost. In a smart home for the disabled, accuracy is important, but accessibility is paramount.

The goal of this research project is to devise an occupancy detection system that forms part of a larger 'smart home for the disabled' that meets the following accessibility criteria;

- *Low Cost*: The set of components required should aim to minimise cost, as these devices are intended to be deployed in situations where the serviced user may be financially restricted.
- *Non-Invasive*: The sensors used in the system should gather as little information as necessary to achieve the detection goal; there are privacy concerns with the use of high-definition sensors.
- *Energy Efficient*: The system may be placed in a location where there is no access to mains power (i.e. roof), and the retrofitting of appropriate power can be difficult; the ability to survive for long periods on only battery power is advantageous.
- *Reliable*: The system should be able to operate without user intervention or frequent maintenance, and should be able to perform its occupancy detection goal with a high degree of accuracy.

Success in this project would involve both

1. Devising a bill of materials that can be purchased off-the-shelf, assembled without difficulty, on which a software platform can be installed that performs analysis of the sensor data and provides a simple answer to the occupancy question, and
2. Using those materials and softwares to create a final demonstration prototype whose success can be tested in controlled and real-world conditions.

This system would be extensible, based on open standards such as REST or CoAP, [9][14] and could easily fit into a larger ‘smart home for the disabled’ or internet-of-things system.

A.3 Method

Achieving these aims involves performing research and development in several discrete phases.

A.3.1 Hardware

A list of possible sensor candidates will be developed, and these candidates will be ranked according to their adherence to the four accessibility criteria outlined above. Primarily the sensor ranking will consider the cost, invasiveness and reliability of detection, as the sensors themselves do not form a large part of the power requirement.

Similarly, a list of possible embedded boards to act as the sensor’s host and data analysis platform will be created. Primarily, they will be ranked on cost, energy efficiency and reliability of programming/system stability.

Low-powered wireless protocols will also be investigated, to determine which is most suitable for the device; providing enough range at low power consumption to allow easy and reliable communication with the hardware.

Once promising candidates have been identified, components will be purchased and analysed to determine how well they can integrate.

A.3.2 Classification

Depending on the final sensor choice, relevant experiments will be performed to determine the classification algorithm with the best occupancy determina-

tion accuracy. This will involve the deployment of a prototype to perform data gathering, as well as another device/person to assess ground truth.

A.3.3 Robustness / API

Once the classification algorithm and hardware are finalised, an easy to use API will be developed to allow the data the device collects to be integrated into a broader system.

The finalised product will be architected into a easy-to-install software solution that will allow someone without domain knowledge to use the software and corresponding hardware in their own environment.

A.4 Timeline

Date	Task
Fri 15 August	<i>Project proposal and project summary due to Coordinator</i>
August	Hardware shortlisting / testing
25–29 August	<i>Project proposal talk presented to research group</i>
September	Literature review
Fri 19 September	<i>Draft literature review due to supervisor(s)</i>
October - November	Core Hardware / Software development
Fri 24 October	<i>Literature Review and Revised Project Proposal due to Coordinator</i>
November - February	<i>End of year break</i>
February	Write dissertation
Thu 16 April	<i>Draft dissertation due to supervisor</i>
April - May	Improve robustness and API
Thu 30 April	<i>Draft dissertation available for collection from supervisor</i>
Fri 8 May	<i>Seminar title and abstract due to Coordinator</i>
Mon 25 May	<i>Final dissertation due to Coordinator</i>
25–29 May	<i>Seminar Presented to Seminar Marking Panel</i>
Thu 28 May	<i>Poster Due</i>
Mon 22 June	<i>Corrected Dissertation Due to Coordinator</i>

A.5 Software and Hardware Requirements

A large part of this research project is determining the specific hardware and software that best fit the accessibility criteria. Because of this, an exhaustive list of software and hardware requirements are not given in this proposal.

A budget of up to \$300 has been allocated by my supervisor for project purchases. Some technologies with promise that will be investigated include;

Raspberry Pi Model B+ Small form-factor Linux computer

Available from <http://arduino.cc/en/Guide/Introduction>; \$38

Arduino Uno Small form-factor microcontroller

Available from <http://arduino.cc/en/Main/arduinoBoardUno>; \$36

Panasonic Grid-EYE Infrared Array Sensor

Available from <http://www3.panasonic.biz/ac/e/control/sensor/infrared/grid-eye/index.jsp>; approx. \$33

Passive Infrared Sensor

Available from various places; \$10–\$20

A.6 Proposal References

- [1] Arduino. <http://arduino.cc/en/Guide/Introduction>. Accessed: 2014-08-09.
- [2] Raspberry pi. <http://www.raspberrypi.org/>. Accessed: 2014-08-09.
- [3] AUSTRALIAN BUREAU OF STATISTICS. 4602.2 - household water and energy use, victoria: Heating and cooling. Tech. rep., October 2011.
- [4] BALAJI, B., XU, J., NWOKAFOR, A., GUPTA, R., AND AGARWAL, Y. Sentinel: occupancy based hvac actuation using existing wifi infrastructure within commercial buildings. In *Proceedings of the 11th ACM Conference on Embedded Networked Sensor Systems* (2013), ACM, p. 17.
- [5] BELTRAN, A., ERICKSON, V. L., AND CERPA, A. E. Thermosense: Occupancy thermal based sensing for hvac control. In *Proceedings of the 5th ACM Workshop on Embedded Systems For Energy-Efficient Buildings* (2013), ACM, pp. 1–8.
- [6] CHAN, M., CAMPO, E., ESTÈVE, D., AND FOURNIOLS, J.-Y. Smart homescurrent features and future perspectives. *Maturitas* 64, 2 (2009), 90–97.
- [7] ERICKSON, V. L., ACHLEITNER, S., AND CERPA, A. E. Poem: Power-efficient occupancy-based energy management system. In *Proceedings of the 12th international conference on Information processing in sensor networks* (2013), ACM, pp. 203–216.
- [8] ERICKSON, V. L., BELTRAN, A., WINKLER, D. A., ESFAHANI, N. P., LUSBY, J. R., AND CERPA, A. E. Thermosense: thermal array sensor networks in building management. In *Proceedings of the 11th ACM Conference on Embedded Networked Sensor Systems* (2013), ACM, p. 87.
- [9] GUINARD, D., ION, I., AND MAYER, S. In search of an internet of things service architecture: Rest or ws-*? a developers perspective. In *Mobile and Ubiquitous Systems: Computing, Networking, and Services*. Springer, 2012, pp. 326–337.

- [10] HAILEMARIAM, E., GOLDSTEIN, R., ATTAR, R., AND KHAN, A. Real-time occupancy detection using decision trees with multiple sensor types. In *Proceedings of the 2011 Symposium on Simulation for Architecture and Urban Design* (2011), Society for Computer Simulation International, pp. 141–148.
- [11] HNAT, T. W., GRIFFITHS, E., DAWSON, R., AND WHITEHOUSE, K. Doorjamb: unobtrusive room-level tracking of people in homes using doorway sensors. In *Proceedings of the 10th ACM Conference on Embedded Network Sensor Systems* (2012), ACM, pp. 309–322.
- [12] KLEIMINGER, W., BECKEL, C., DEY, A., AND SANTINI, S. Using unlabeled wi-fi scan data to discover occupancy patterns of private households. In *Proceedings of the 11th ACM Conference on Embedded Networked Sensor Systems* (2013), ACM, p. 47.
- [13] KLEIMINGER, W., BECKEL, C., STAAKE, T., AND SANTINI, S. Occupancy detection from electricity consumption data. In *Proceedings of the 5th ACM Workshop on Embedded Systems For Energy-Efficient Buildings* (2013), ACM, pp. 1–8.
- [14] KOVATSCH, M. Coap for the web of things: from tiny resource-constrained devices to the web browser. In *Proceedings of the 2013 ACM conference on Pervasive and ubiquitous computing adjunct publication* (2013), ACM, pp. 1495–1504.
- [15] TING, K., YU, R., AND SRIVASTAVA, M. Occupancy inferencing from non-intrusive data sources. In *Proceedings of the 5th ACM Workshop on Embedded Systems For Energy-Efficient Buildings* (2013), ACM, pp. 1–2.
- [16] YANG, Z., LI, N., BECERIK-GERBER, B., AND OROSZ, M. A multi-sensor based occupancy estimation model for supporting demand driven hvac operations. In *Proceedings of the 2012 Symposium on Simulation for Architecture and Urban Design* (2012), Society for Computer Simulation International, p. 2.

Bibliography

- [1] Arduino. <http://arduino.cc/en/Guide/Introduction>. Accessed: 2014-08-09.
- [2] Raspberry pi. <http://www.raspberrypi.org/>. Accessed: 2014-08-09.
- [3] AUSTRALIAN BUREAU OF STATISTICS. Household water and energy use, Victoria: Heating and cooling. Tech. Rep. 4602.2, October 2011.
- [4] BALAJI, B., XU, J., NWOKAFOR, A., GUPTA, R., AND AGARWAL, Y. Sentinel: occupancy based HVAC actuation using existing WiFi infrastructure within commercial buildings. In *Proceedings of the 11th ACM Conference on Embedded Networked Sensor Systems* (2013), ACM, p. 17.
- [5] BELTRAN, A., ERICKSON, V. L., AND CERPA, A. E. ThermoSense: Occupancy thermal based sensing for hvac control. In *Proceedings of the 5th ACM Workshop on Embedded Systems For Energy-Efficient Buildings* (2013), ACM, pp. 1–8.
- [6] CHAN, M., CAMPO, E., ESTÈVE, D., AND FOURNIOLS, J.-Y. Smart homes - current features and future perspectives. *Maturitas* 64, 2 (2009), 90–97.
- [7] ERICKSON, V. L., ACHLEITNER, S., AND CERPA, A. E. POEM: Power-efficient occupancy-based energy management system. In *Proceedings of the 12th international conference on Information processing in sensor networks* (2013), ACM, pp. 203–216.
- [8] FISK, W. J., FAULKNER, D., AND SULLIVAN, D. P. Accuracy of CO2 sensors in commercial buildings: a pilot study. Tech. Rep. LBNL-61862, Lawrence Berkeley National Laboratory, 2006.
- [9] HAILEMARIAM, E., GOLDSTEIN, R., ATTAR, R., AND KHAN, A. Real-time occupancy detection using decision trees with multiple sensor types. In *Proceedings of the 2011 Symposium on Simulation for Architecture and Urban Design* (2011), Society for Computer Simulation International, pp. 141–148.

- [10] HNAT, T. W., GRIFFITHS, E., DAWSON, R., AND WHITEHOUSE, K. Doorjamb: unobtrusive room-level tracking of people in homes using doorway sensors. In *Proceedings of the 10th ACM Conference on Embedded Network Sensor Systems* (2012), ACM, pp. 309–322.
- [11] KLEIMINGER, W., BECKEL, C., DEY, A., AND SANTINI, S. Inferring household occupancy patterns from unlabelled sensor data. Tech. Rep. 795, ETH Zurich, 2013.
- [12] LI, N., CALIS, G., AND BECERIK-GERBER, B. Measuring and monitoring occupancy with an RFID based system for demand-driven HVAC operations. *Automation in construction* 24 (2012), 89–99.
- [13] SERRANO-CUERDA, J., CASTILLO, J. C., SOKOLOVA, M. V., AND FERNÁNDEZ-CABALLERO, A. Efficient people counting from indoor overhead video camera. In *Trends in Practical Applications of Agents and Multiagent Systems*. Springer, 2013, pp. 129–137.
- [14] TEIXEIRA, T., DUBLON, G., AND SAVVIDES, A. A survey of human-sensing: Methods for detecting presence, count, location, track, and identity. Tech. rep., Embedded Networks and Applications Lab (ENALAB), Yale University, 2010.