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Testing the accuracy of low-cost data streams for determining single-person office occupancy and their use for energy reduction of building services

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A B S T R A C T

We explored methods of detecting occupancy in single-person offices using data already collected by the occupant's PC, or data from relatively cheap sensors added to the PC. We collected data at 15-s intervals for up to 31 days in each of 28 offices. A combination of low/no cost sensors (webcam-based motion detection, and keyboard and mouse activity) was much more accurate at detecting occupancy than a commercial ceiling-based passive infrared (PIR) sensor, and provided overall daytime accuracy >90%, with very low false negative rates. This enhanced detection performance would enable a reduction in the timeout periods for building service curtailment on space vacancy. For example, lighting switch-off timeout could be reduced from the current energy code standard of 20 min to less than 5 min, increasing energy savings potential by 25–45%. We then deployed this system in a proof-of-concept demonstration, using it to control lighting, heating, ventilation, and air conditioning (HVAC), and plug loads in a mock-up office environment. Tests were run over nine occupied days (six in cooling season, three in heating season). The system delivered energy savings of 15–68%, with no reported false negative errors.

1. Introduction

The key to saving energy in buildings is to deliver building services only when and where they are needed, in the amount they are needed. Occupancy sensor technology and related controls have emerged from this observation. Occupancy sensors have been deployed at the room level to save energy primarily in ambient lighting systems [32,8], with the potential for energy savings with HVAC systems also emerging [5]. Energy savings of 20–50% are typically reported.

Given this success, occupancy sensors for lighting systems are now mandated in certain space types in many energy codes for new buildings (e.g. [2]). However, penetration of this technology as a retrofit in existing buildings is low, and first-cost remains a tangible barrier. The goal of our research was to lower this cost barrier by extracting free or nearly-free occupancy information from an office PC platform. The attraction of a PC platform is that it is already in place in an office environment, and is already powered and networked.

Extracting occupancy data from systems not explicitly designed to deliver occupancy information has been termed "implicit occupancy sensing" [19]. Examples of implicit occupancy data include: computer network activity (e.g. [13]), security card access systems (e.g. [10]), detection of mobile devices at Wi-Fi access points (e.g. [12]), and PC-based sources such as keyboard activity, webcams, and microphones. These data streams may be supplemented by environmental sensors (e.g. temperature, humidity, light, sound), which are already present in some computing platforms, and are expected to become more widespread as wireless nodes lower in cost and become pervasive as part of the "Internet of Things" (IoT). Although these channels might provide limited accuracy in detecting occupancy independently, their aggregated data may carry more precision and robustness than any one high-end sensor [5,28,11,10].

Many studies addressing alternative means of detecting occupancy were summarized in [26]. However, few prior studies have focussed specifically on use of implicit data sources and supplemental environmental sensors in single-person office spaces, with no requirement for the occupant to carry hardware on their person.

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Zhao et al. [35] collected data in two offices over several weeks. Keyboard and mouse data were collected every 20 s along with data from supplemental sensors: PIR, chair pressure, door open/shut, lighting on/off, Wi-Fi connection, and GPS location. Bayesian Belief Networks were used to select the optimal fusion of sensor data, which typically involved keyboard, mouse and PIR data streams. Ground truth was derived from three extra PIR sensors and occupant diary entries. Overall accuracy exceeded 90%

Hailemariam et al. [11] added light, sound, CO_2, current, and motion sensors to a single office cubicle; the motion sensor was mounted on the cubicle wall close to and facing the occupant. Data were aggregated at the 1-min level and collected over one week. Ground truth occupancy was obtained from human transcription of video images. Using a decision-tree method, an overall detection accuracy of 98% was achieved.

Nguyen & Aiello [22] used environmental sensors to infer not only office occupancy, but also the activity type (presence, absence, working with PC working without PC, and having a meeting). They relied on a pressure sensor in the chair, a ceiling mounted PIR sensor, and two acoustic sensors (one placed to register conversation and a second placed to register keyboard/mouse use). The user kept an activity diary every 5 min to provide ground truth. A test in a single office over five days yielded activity detection accuracy of 95%.

While not explicitly measuring the accuracy of an alternative occupancy sensing approach, Dalton and Ellis [36] provided a very relevant application. They used a webcam with a simple face detection algorithm to determine if someone is looking at a PC display, and to switch off the display if no-one is looking at it. Their very short experiments suggested display energy savings of 12–30% compared to a fixed power saving mode enacted after five minutes of no PC activity.

We conducted a field study to test the accuracy of various data streams for determining the occupancy of offices, and determined a combination of PC-based sensor data streams that substantially outperformed the incumbent commercial technology. We then deployed the system in a full-scale demonstration to control several office systems (lighting, HVAC, miscellaneous/plug loads[1]) over multiple test days in heating and cooling seasons. This research is an advance over previous work in several important aspects:

- Data collection in more offices and over a longer time period
- More accurate ground truth recording
- Direct comparison to incumbent commercial technology
- Separate consideration of false positive and false negative error types
- Focus on accuracy during normal working hours only, when information is most relevant
- Demonstration of actual control of building services based on the new approach.

2. Better occupancy sensing

2.1. Methods & procedures

2.1.1. Sensor and data description

We installed hardware and software on the PCs of volunteers who occupied single-person office spaces; we also installed additional hardware in these offices spaces. We recorded data from a variety of different sources that may indicate occupancy:

1. Keyboard and mouse activity. We recorded only if these devices had been used, not what was typed or clicked.
2. Webcam (external retrofit,[2]). We mathematically derived pixel value differences in consecutive frames of down-sampled images[3] we did not record or store images.
3. Microphone (external retrofit,[4] Phidgets 1133). We recorded only dB levels, not what was said.
4. Infra-red sensor (Omron D6T-44L). Low-res (4 × 4) pixel temperature map of the space.
5. Proximity sensor (MaxBotix EZ-1). Distance from sensor to nearest solid object.
6. Air Temperature and Relative Humidity (Phidgets 1125).
7. Light Level (Phidgets 1142).
8. PIR motion sensor (Phidgets 1111).
9. Commercial, PIR motion sensor (Manufacturer name/model withheld).
10. Pressure mat (United Security 925).[5] This was used as "ground truth".

Sensors 1–8 were already present in the PC, or were mounted to the PC monitor (Fig. 1); Sensor 9 was mounted on the ceiling in a typical location for commercial use; Sensor 10 covered the majority of the most frequently occupied floor space in the office. The external webcam was connected to the PC via a dedicated USB port; other PC-based sensors that were not internal were connected to a data acquisition board, and then to the PC via a single USB port.[6]

Data from all sensors were recorded and collated by custom software on each PC whenever the PC was switched on.[7] Data were recorded every 15 s, and were a statistical summary (e.g. Counts, Max, Min, Mean, Median) of raw data recorded at 1 or 5 Hz. The term "row" of data below refers to a single 15-s instance of data from one participant, that instance containing the statistical summary of data from all sensors.

2.1.2. Participants and data collection period

There were 28 participants in the study, located in three mixed-use buildings in Ottawa, Canada. Office ID codes and descriptions are shown in Table 1. Data collection occurred during July–October 2013. Table 1 shows the number of days of raw (original) and final (cleaned) data available.

2.1.3. Data cleaning

We observed some instances when the pressure mat signal indicated extended occupancy though it was clear there was no-one present (e.g. overnight). This could occur if a very heavy object was placed on the mat or if the occupant's office chair was wedged under their desktop to apply continuous downward pressure. We removed entire days of data from all sensors if the day contained

[1] In an office setting, these are any electrical device powered from a conventional wall socket, and may include: computers, monitors, printers, fans, external speakers, supplemental space heaters, desk lights, coffee machines etc. (e.g. [20]).

[2] We used an external webcam because not all PCs in the study group had internal webcams, but a future low-cost application would leverage ubiquitous internal webcams.

[3] Utilizing the Windows API, consecutive (40 × 30 pixel) images were captured every second from the webcam. The distance in RGB space between the two images for each image pixel was calculated:

$$d(x, y)_{0-255} = \sqrt{\left((R_2 - R_1)^2 + (G_2 - G_1)^2 + (B_2 - B_1)^2\right)/3}$$

and a simple metric for motion detection was the maximum distance among all pixels.

[4] We used an external microphone because not all PCs in the study group had internal microphones, but a future low-cost application would leverage ubiquitous internal microphones.

[5] Mat sensitivity was chosen to ensure that an empty chair or full briefcase would not trigger it.

[6] The radar sensor shown in Fig. 1 was only installed on 15 of the sample PCs, and thus was not utilized in further analysis.

[7] The software continued to record data even if the host computer went into a "standby" or "sleep" mode.