"Converging Redundant Sensor Network Information for Improved Building Control"

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Abstract

This project is investigating the development and application of sensor networks to enhance building energy management and security. Commercial, industrial and residential buildings often incorporate systems used to determine occupancy, but current sensor technology and control algorithms limit the effectiveness of these systems. For example, most of these systems rely on single monitoring points to detect occupancy, when more than one monitoring point would improve system performance.

Phase I of the project focused on instrumentation and data collection. In Phase I, a new occupancy detection system was developed, commissioned and installed in a sample of private offices and open-plan office workstations. Data acquisition systems were developed and deployed to collect data on space occupancy profiles.

In phase II of the project, described in this report, we demonstrate that a network of several sensors provides a more accurate measure of occupancy than is possible using systems based on single monitoring points. We also establish that analysis algorithms can be applied to the sensor network data stream to improve the accuracy of system performance in energy management and security applications, and show that it may be possible to use sensor network pulse rate to distinguish the number of occupants in a space.

Finally, in this phase of the project we also developed a prototype web-based display that portrays the current status of each detector in a sensor network monitoring building occupancy. This basic capability will be extended in the future by applying an algorithm-based inference to the sensor network data stream, so that the web page displays the likelihood that each monitored office or area is occupied, as a supplement to the actual status of each sensor.

Table of Contents

1 Introduction **1**
1.1 Background 1
2 Executive summary **3**
3 Experimental **4**
3.1 Study I: Comparison of Sensor Network Performance with Human Observers and Video Recording 4
3.1.1 Methods and Procedures 4
3.1.2 Results 5
3.2 Study II: Performance of Sensor Networks for Monitoring Occupancy in Private Offices 9
3.2.1 Methods and Procedures 9
3.2.2 Results 11
3.3 Study III: Sensor Network Firing Rate and Occupancy in an Open-Plan Office 13
3.3.1 Methods and Procedures 13
3.3.2 Results 14
4 Conclusions **15**
5 References **18**
6 List of Acronyms and Abbreviations **19**
7 Acknowledgements **20**

List of Graphical Materials

Figure 1: Detail of room 2 occupancy profile from morning of day 2 as measured by human observer (top panel), video image (middle panel) and PIR sensor network (bottom panel) .6
Figure 2: Frequency of unoccupied intervals received from sensor network monitoring one office during occupied periods over a single day 7
Figure 3: Frequency of unoccupied intervals received from sensor network monitoring two offices during occupied periods over two days 8
Figure 4: Percent deviation from occupancy as a function of sensor network silent interval 8
Figure 5: Data acquisition and control systems used in second study 9
Figure 6: Cumulative occupied time (mins) as measured by PIR sensor network over two month monitoring period 12
Figure 7: Total occupied minutes per day (10 private offices over 2 months) 13
Figure 8: Total occupied minutes per hour (10 private offices over 2 months) and effect on occupied time of sensor network silent interval 13
Figure 9: Plan view of open-plan office layout 14
Figure 10: Relationship between PIR sensor pulse rate and occupancy over two days in an open-plan office 15
Figure 11: Web page displaying status of PIR sensors located in ten private offices..........16

1 Introduction

1.1 Background

This technical progress report describes results from the second phase of a three-phase project to design, implement, validate, and prototype new technologies to monitor occupancy, control indoor environment services, and promote security in buildings. Commercial, industrial and residential buildings often incorporate systems used to determine occupancy, but current sensor technology and control algorithms limit the effectiveness of these systems. More effective building services will be facilitated through more extensive occupancy sensing systems, and more sophisticated analysis of sensor data, which in this project are achieved by:

- Development of low-cost distributed sensor networks. The delivery and management of building indoor environment services (e.g., lighting, heating, ventilating and air conditioning [HVAC] and, security systems), will be improved if control systems are based on systems of multiple independent distributed occupancy detectors, instead of relying on single points of occupancy detection, and;
- Development of new analysis methods and control algorithms to treat data arising from distributed sensor networks. Collecting information from a network of sensors is only advantageous if accompanied by a rational analysis framework that can be used to make inferences about occupancy from the resulting data stream.

Many occupancy-based control systems currently deployed in buildings use passive infrared (PIR) and/or ultrasonic technologies, signaling space occupancy based on changes in the temperature or sound profile of the space. In energy management applications, the occupancy sensor functions as a timer, sending a signal to a switch that turns off electrical power after a defined period of time has elapsed during which no signal has been received from the detector (e.g., switch lights off when the space has been unoccupied for 20 minutes). In security applications, an "armed" system initiates a security call immediately upon receiving a signal from a single detector. In conventional systems, as soon as a signal is received, occupancy is assumed without further analysis of signals from the same sensor or taking into account any other available information. Current systems do not differentiate between one or more occupants in a monitored space, although this capability would be useful for energy management and security.

Commercially available occupancy-based control systems compensate for the uncertainty associated with single points of detection using a parameter that sets a relatively long interval that must elapse before initiating the appropriate control action (e.g., switch the lights off after the space has been unoccupied for 20 minutes), to ensure that services are not inadvertently switched off in an occupied space. The duration of this interval is crucial to energy savings and occupant acceptance alike. It may be possible to set a much shorter interval using a network of sensors with appropriate analysis and control software instead of a single detector.

The first phase of this project focused on instrumentation and data collection. In Phase I, a new occupancy detection system was developed, commissioned and installed in a sample of private offices and open-plan office workstations. Data acquisition systems were developed and deployed to collect data on space occupancy profiles. These data provided the foundation for the work completed in Phase II.

In Phase II of the project, described in this report, we show that a network of several sensors provides more accurate occupancy determination than is possible with a single monitoring point. (Tiller, Henze & Guo, 2005). We also demonstrate that it is possible to specify analysis algorithms that can be applied to the sensor network data stream to improve the accuracy of system occupancy determination.

Also in Phase II, we evaluated the application of belief network models to the raw data collected during the first phase. A technical paper describing the results of this work has been prepared (Dodier, Henze, Tiller & Guo, 2005), submitted to the journal *Energy and Buildings*, and is currently under review. While this work showed that belief network analysis provides a sophisticated paradigm for determining occupancy from a sensor network, it also showed that the belief network was computationally intensive. Our implementation of the belief network algorithm was not able to complete the required computations within the time slice currently being analyzed. Although future developments in computing hardware power and speed will eventually lead to a resolution of this issue, the application of belief networks to this area may not be practical at this time. Nevertheless, we do not plan to abandon the belief network paradigm as we still believe it offers the most comprehensive and elegant conceptual framework for treating sensor network data.

Consequently, we propose an alternative control algorithm, which we are still evaluating. This algorithm is based on the observation that it is possible to achieve good agreement between sensor network response and actual occupancy by taking into account sensor network signals that indicate occupancy, *and* the duration and frequency of time intervals that the space was actually occupied, but during which the sensor network indicated it was vacant (subsequently referred to as "sensor network silence").

Most short duration periods of sensor network silence (e.g., less than two minutes duration, in which we might conclude that the space was vacant), actually occur when the space is occupied. In contrast, longer periods of sensor network silence (e.g., longer than five minutes duration) are likely accurate, indicating that the space is indeed vacant. Hence, it should be possible to ignore short-duration "unoccupied" intervals of sensor network silence, as the probability is high that the space is still occupied. The duration of the sensor network silent interval can be used in a control algorithm to objectively define the time interval that must elapse before the system initiates a control action. We are currently developing software that incorporates this parameter, and are collecting data that will allow us to evaluate the effectiveness of this control strategy, based on the accuracy of this method to predict occupancy when applied to a data set with a known occupancy profile.

Current systems do not differentiate between one or more occupants in a monitored space, although this capability would be useful for energy management and security. For example, the effectiveness of HVAC systems could be improved by modulating airflow to spaces as a function of the number of occupants, and it would be useful for emergency first responders to know the location and numbers of occupants in a building. We report preliminary results that show it may be possible to use sensor network pulse rate to distinguish the number of occupants in an open-plan office space.

Finally, in Phase II we also developed a prototype web-based display that portrays the current status of each detector in a sensor network monitoring building occupancy. In the future, we plan to extend this basic capability by applying probabilistic inference to the sensor network data stream, so that the web page displays a probabilistic judgment concerning the likelihood that each monitored office or area is occupied, as a supplement to the actual status of each sensor.

2 Executive summary

This project is based on the simple idea that it makes good sense to switch off building services (lighting, ventilation, miscellaneous electrical plug loads) when spaces are unoccupied. Current building practice incorporates many environmental control features: occupancy detectors that switch lights on and off, and centralized building energy management and control systems are two examples. However, sensor technology and control algorithms limit the effectiveness of current systems.

More effective indoor environmental control and building management will be facilitated through more extensive sensing, and more sophisticated analysis of sensor data. More extensive sensing means the development and deployment of low-cost distributed sensor networks, in contrast to current technology that relies on single points of measurement. More sophisticated analysis of sensor data means the development of an analysis framework that can be applied to the sensor network data stream to make accurate inferences about occupancy. Phase I of the project (Tiller & Henze, 2004) focused on Instrumentation and Data Collection. Field trials were conducted to collect the raw data required to identify promising combinations of new and existing low cost sensors that we expect will improve system performance

In Phase II of the project we show that a network of several sensors provides more accurate occupancy determination than is possible using systems based on single monitoring points. Sensor networks consisting of three PIR sensors were installed in private offices occupied by faculty at the University of Nebraska's Peter Kiewit Institute, located in Omaha, NE, U.S.A. Two studies monitoring occupancy showed that sensor position and aiming were key for determining whether or not a monitored space was occupied. The mean difference in occupied time measured by three PIR sensors installed in each of ten private offices monitored for two months was 44.7 % (range 16% - 74%).

Further analysis of the sensor network data stream during occupied intervals suggested a relatively simple algorithm that can be applied to improve the accuracy with which the sensor network determines occupancy. Good agreement between sensor network response and actual occupancy can be achieved by taking into account sensor network signals that indicate occupancy, *and* the duration and frequency of time intervals that the space was actually occupied, but during which the sensor network indicated it was vacant. We are currently developing software that incorporates this parameter, and are collecting data that will allow us to evaluate the effectiveness of this control strategy.

Current systems do not differentiate between one or more occupants in a monitored space, although this capability would be useful for energy management and security. We report preliminary analysis of data collected from an open-plan office area hosting 23 cubicle workstations (each of which was monitored by 3 PIR sensors) that shows a clear linear relationship between sensor pulse rate and the number of occupants in the space. The coefficient of determination (r^2) for the linear regression model relating these two variables was 0.672. Even though the model relating these two variables was very simple, it shows a clear relationship and predictive value, and it may be possible to increase the predictive power of the model by including other variables in a multiple regression model.

Finally, in Phase II we also developed a prototype web-based display that portrays the current status of each detector in a sensor network monitoring building occupancy. In the future, we plan to extend this basic capability by applying an inference based on the analysis algorithm to the sensor network data stream, so that the web page displays a probabilistic judgment concerning the likelihood that each monitored office or area is occupied, as a supplement to the actual status of each sensor.

3 Experimental

This section describes three studies that were conducted during Phase II. The first study involved two private offices, and compared the performance of a sensor network with two other independent methods of occupancy detection. The second study involved a larger sample of offices, and confirmed and extended some of the results reported in the first study. The third study, still currently ongoing, examined the relationship between sensor network pulse rate and occupancy in an open-plan office.

3.1 Study I: Comparison of Sensor Network Performance with Human Observers and Video Recording

A sensor network was designed, installed, and tested in two, 3m x 4m private offices, over a period of two days. The offices were occupied by faculty at the University of Nebraska's Peter Kiewit Institute, located in Omaha, NE, U.S.A. The sensor network consisted of three commercially-available PIR occupancy sensors, aimed at occupied areas in the work space. Each sensor provides an independent measure of space occupancy, and taken together, the combination of measurements provides a converging and redundant sensor network. The sensor network data were validated by comparing occupancy as determined by the PIR sensors with two other independent measures: occupancy as recorded by human observers, and a digital video camera continuously collecting images in each office.

3.1.1 Methods and Procedures

The three PIR sensors in each office (six sensors in total) were connected to a USB PC-based data acquisition system manufactured by Data Translation, model number DT9806. The electrical signals from the PIR sensors were connected to the digital inputs on the DT9806 terminal block. The data acquisition and control software was developed using the Data Translation Measure Foundry programming environment. This data acquisition system polled each PIR sensor every second, writing a single character to a text file to indicate whether or not each respective detector was sending a signal to indicate occupancy (a "0" indicates no signal from the detector, and a "1" indicates a signal – and assumed occupancy – from the detector). A more complete description of the data acquisition systems used in this study is provided in the Phase 1 Technical Progress Report (Tiller & Henze, 2004).

The sensor network data were validated by comparing occupancy as determined by the PIR sensors with two independent measures: occupancy as recorded by human observers, and a digital video camera continuously collecting images in each office.

Occupancy was monitored over the two-day period by three human observers. One of the three individuals was always present between the hours of 7:00am to 7:00pm on both days. Both monitored offices were simultaneously visible from the vantage point of the human observer: a large piece of black electrical tape was mounted on the doorframe of each office being monitored, to ensure that the observers only recorded entry and exit from the offices of interest, and not from adjacent rooms. The human observer recorded the time associated with all occupant entry and exit events occurring over the two-day period.

The human observations and PIR data were complemented by a digital video record of office occupancy. Apple iSight digital video cameras were mounted in each office diagonally opposite the single door, providing a clear record of each entry and exit event. The software controlling each camera recorded the date and time of each image (in date:hour:minute:second format), writing this information clearly in the lower right area of each image frame. A separate image was collected every two seconds, and these separate images were automatically appended to a QuickTime file, which provided a time-lapse movie showing activity in each room over the two-day monitoring period. The time-lapse movies were manually reviewed by a human observer, who recorded occupant entry and exit times.

3.1.2 Results

There were 43 occupancy events in Room 1 and 36 events in Room 2 over the two day monitoring period. Slight differences in event time and duration were apparent in the occupancy data recorded by each method. These are due to asynchrony between the clocks used to record events by the human observers, the computers collecting PIR data, and digital video images. Although an attempt was made to closely synchronize all clocks, it was not possible to achieve exact synchrony.

Human observers also made transcription errors related to some events: for example, in one case the human observer incorrectly noted an event ending on minute 23, when the other two methods showed the event ending sometime between 16:31 and 16:33. In this case we infer that the human observer incorrectly recorded "23" instead of "32". In Room 1, 10 out of 86 start/end times were modified to correct transcription errors, and in Room 2, 8 out of 62 start/end times were so modified. Digital image collection was not initiated in Room 1 until 8:39am, and in Room 2 until 9:52am, so several events are missing from the digital video records for the first day. Finally, one of the detectors in Room 1 (PIR3) was defective (intermittent firing overnight when no one was present), and so data from this detector were excluded from the analysis.

Table 1 shows the cumulative time (in seconds) that each room was occupied, as measured by individual PIR sensors along with the percentage difference in occupied time, as measured by each detector. Although the three sensors were aimed at the center occupied area in each office, sensor position was vital for determining whether or not the space was occupied. In the most extreme case, there was a 76.4% difference in the cumulative occupied time, as measured by PIR1 versus PIR3 in Room 2 on the second day.

Table 1. Cumulative occupied time (s) as measured by PIR sensors

	Room 1 Day 1	Room 1 Day 2	Room 2 Day 1	Room 2 Day 2
PIR1	7021	6889	16709	6193
PIR2	11517	13080	25384	9540
PIR3[(1)]	**21058**	**23388**	6901	2254
Percent Difference[(2)]	39.0%	47.3%	72.8%	76.4%

1. Values for PIR3 (bold type) were not included in analysis as this detector was faulty.
2. Percent difference was calculated as (max-min)/max.

The resulting control actions would also have differed, depending on detector location.

Table 2 shows the cumulative time (in seconds) that each room was occupied, as measured by the PIR sensor network, human observer and the video image. The PIR sensor network made a determination of occupancy if one of the three detectors in the space fired at the second polling was initiated by the data acquisition system: these values are referred to in Table 2 as the PIR Composite signal.

Table 2. Cumulative occupied time (s) as measured by PIR sensor network, human observer and video image

	Room 1 Day 1	Room 1 Day 2	Room 2 Day 1	Room 2 Day 2
Human Observer	17723	16789	33881	11494
Video Image	15085	16766	25829	11543
PIR Composite	13011	14050	26712	9823
PIR Smoothed	17827	16979	34125	11538

The differences in cumulative occupied time as identified by the different measurement methods are large, but these are easy to explain. For example, Table 2 shows a 36% difference in occupancy for Room 1 Day 1 as noted by the human observer (17,723 seconds or 4.9 hours) versus the PIR Composite data (13,011 seconds or 3.6 hours). The data collected by the human observer show all elapsed time during occupied intervals, whereas the PIR Composite data show cumulative seconds in which all detectors in the space fired at the second polling was initiated by the data acquisition system. Consequently, the PIR Composite data do not uniformly show occupancy through the duration of any occupied interval as recorded by a human observer. This is apparent in Figure 1, which depicts occupancy data collected during the morning of Day 2 from Room 2: note the spikes in the PIR Composite data record within each occupied interval, compared to the data from the human observers and the digital video.

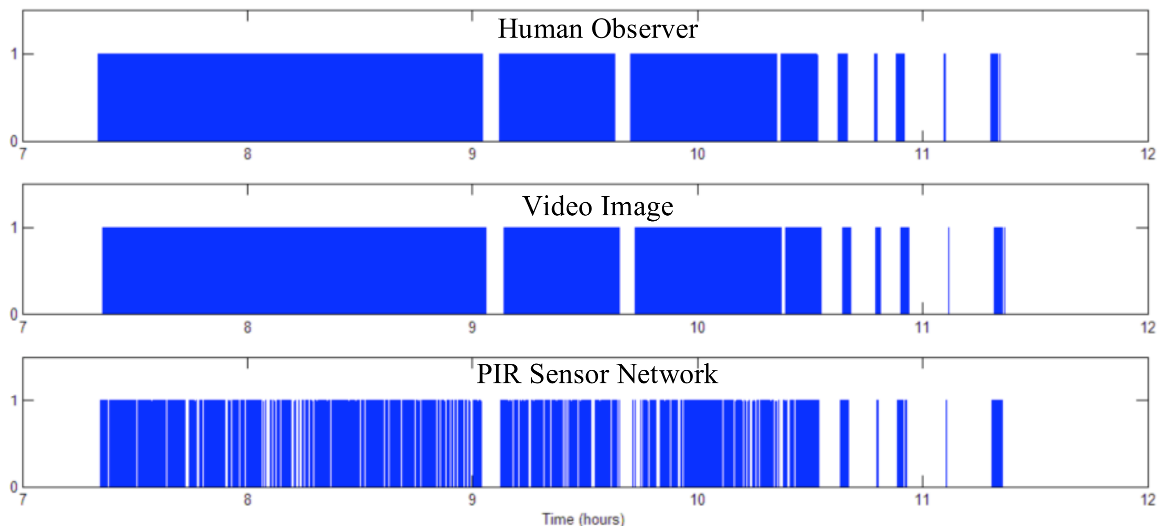

Figure 1: Detail of room 2 occupancy profile from morning of day 2 as measured by human observer (top panel), video image (middle panel) and PIR sensor network (bottom panel)

Recoding the PIR Composite data to show continuous occupancy within any given event improves the agreement between the different methods. The PIR data so recoded are referred to as "PIR Smoothed" in Table 2, and as a consequence, the 36% difference reported above is reduced to a difference of less than 1%.

This agreement is achieved only through the application of a *post hoc* correction to the sensor network data, based on the information collected by the human observers. This is problematic because it assumes knowledge of the actual occupied state to optimize the performance of the sensor network, which will not be available in a real application. Further analysis shows that it may be possible to use temporal aspects of the sensor network data stream to define an objective measure that can be used to determine if the space is occupied. The proposed method takes into account sensor network signals that indicate occupancy, *and* the duration and frequency of time intervals that the space was actually occupied but during which the sensor network indicated it was vacant (the sensor network silent interval).

Figure 2 shows the frequency of sensor network silent intervals for each sensor in one of the rooms over one day, during periods in which the space was actually occupied, in five-second class intervals. The figure shows that silent intervals of less than 5 seconds in duration can be ignored, as the probablity is high that the space is still occupied. Figure 3 depicts the mean frequency of the silent intervals received from the sensor network monitoring the two offices during occupied periods over two days. As the duration of the silent interval increases, the probablility that the space is actually occupied decreases significantly, and the appropriate control actions related to building systems can be initiated.

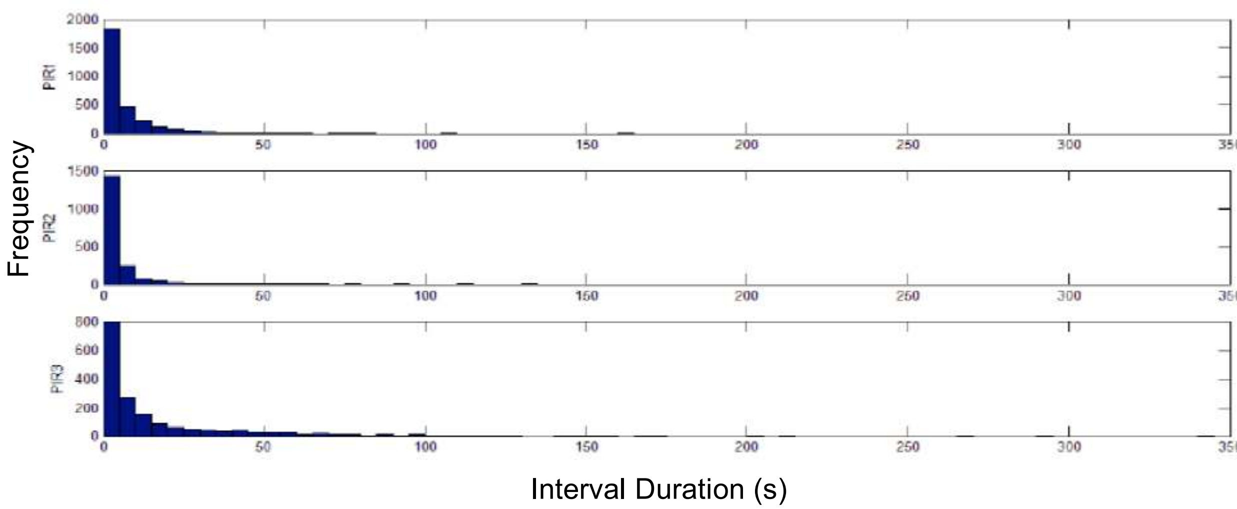

Figure 2: Frequency of unoccupied intervals received from sensor network monitoring one office during occupied periods over a single day

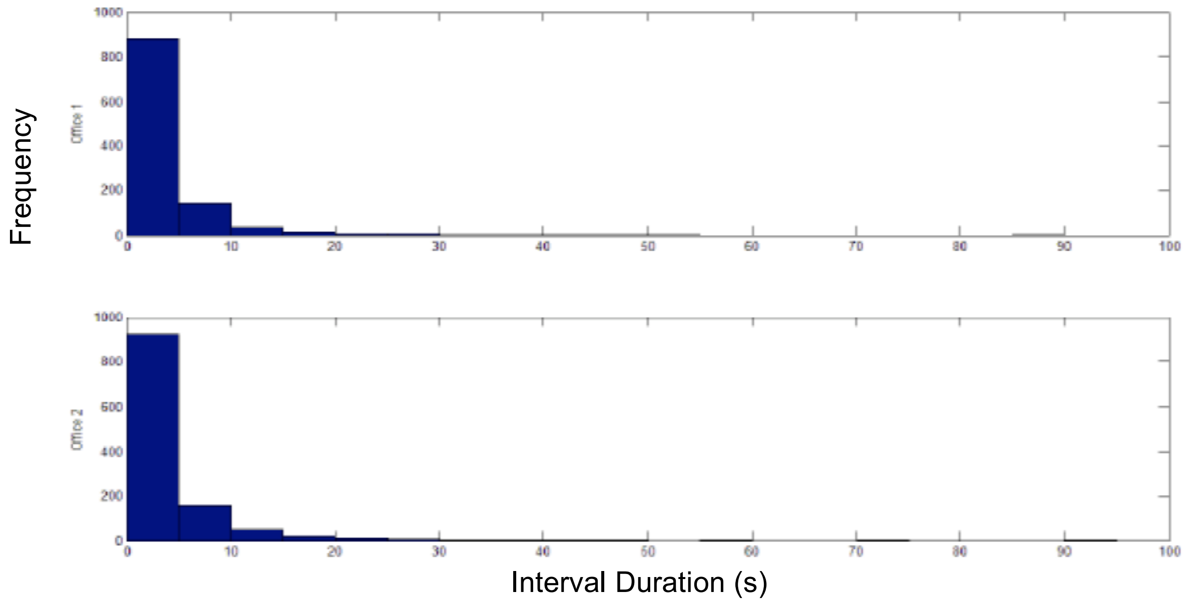

Figure 3: Frequency of unoccupied intervals received from sensor network monitoring two offices during occupied periods over two days

Figure 4 extends this analysis, showing the relationship between the percent deviation from actual occupied time (measured in seconds), as a function of the sensor network silent interval.

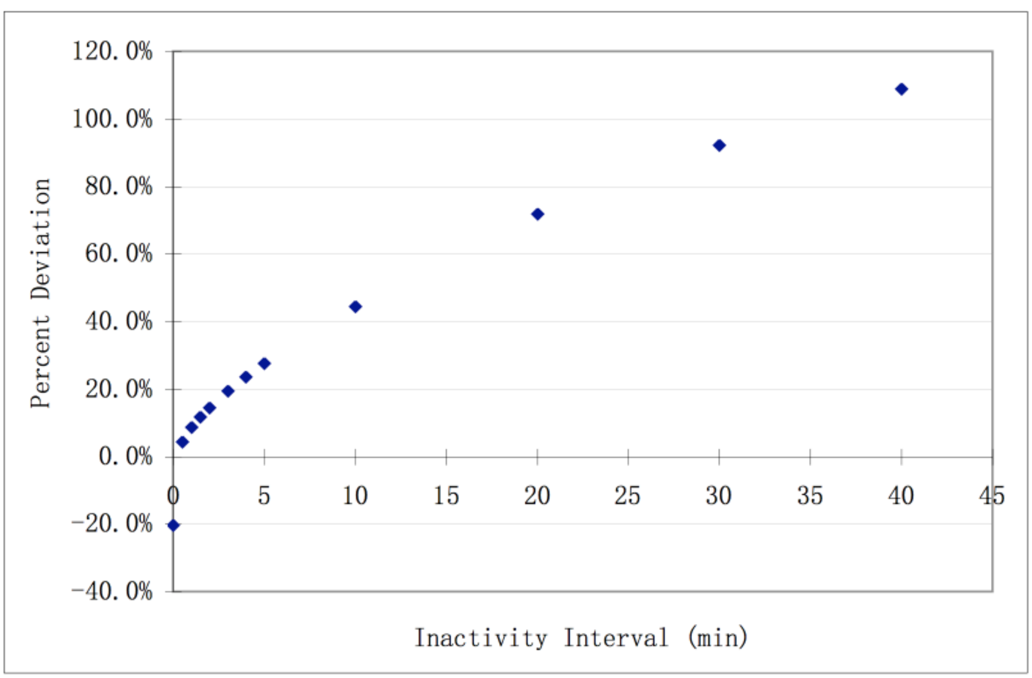

Figure 4: Percent deviation from occupancy as a function of sensor network silent interval

This figure shows that as the sensor network silent interval is increased, the correspondence between actual occupied time and the duration of assumed occupancy (which is the actual occupied time plus the sensor network silent interval) breaks down. As the duration of this interval is increased, the correspondence between actual and assumed occupancy shows an orderly deterioration. It is also interesting to note that in this specific case the raw sensor network data stream actually *underestimates* occupancy. As noted above, this is because the composite signal from the sensor network shows the number of seconds the sensor network showed occupancy at the second polling was initiated by the data acquisition system, which will not necessarily correspond with the duration of any single occupied period.

3.2 Study II: Performance of Sensor Networks for Monitoring Occupancy in Private Offices

A second study was performed to confirm and extend some of the findings reported in the first study, using a larger sample of private offices monitored over two months.

3.2.1 Methods and Procedures

Different sensors and data acquisition systems were used in this study. The systems used in the first study were suitable for collecting data over short periods of time from a small number of PIR sensors, but these systems ultimately proved both unscalable to larger numbers of PIR sensors, and unstable for longer periods of data acquisition.

The PIR sensors used in this study were battery-powered wireless PIR motion detectors that are most commonly used in home automation applications (using the X10 power line carrier communications protocol). The wireless radio frequency signals from the PIR sensors are received by a 310mhz antenna, which is connected via RS232 serial interface to a computer that records the signals from the sensors, using a commercially available home automation control software package called XTension. This software package runs under the Apple Macintosh OS X operating system. This system does not poll all sensors every second. Each sensor instead sends a signal whenever it detects motion. This signal is detected by the antenna, and an entry recording the date, time and unique sensor identification number are recorded in a computer hard disk log file. Once an individual sensor has sent a signal indicating occupancy, six seconds must elapse before it can send another signal. Since each private office contains three PIR sensors, a maximum of 18 signals can be sent to the data acquisition system in any minute. For the purposes of this analysis, when a signal was received from any of the three passive infrared (PIR) sensors in a space, the space was considered occupied for the duration of that minute. Figure 5 depicts the various components of this solution.

Figure 5: Data acquisition and control systems used in second study

The left panel of Figure 5 depicts the PIR occupancy sensor, the middle panel shows a view of the computer system and antenna (at the top left quadrant of the photograph) used to collect and record the signals sent by the wireless PIR sensors, and the right panel shows a detail of the antenna and RS232 serial interface. This data acquisition system has proved to be more scalable and stable than the systems used in the first study, and it is considerably less labor intensive to install because no wire pulling is required.

Sensor networks consisting of three wireless PIR sensors were installed in ten, 3m x 4m private offices, and occupancy data were collected over a period of two months. The offices were occupied by faculty at the University of Nebraska's Peter Kiewit Institute, located in Omaha, NE, U.S.A.

Two analyses are reported here. The first analysis compares the duration of the occupied intervals in the ten offices as measured by the individual detectors. The second analysis models the effects of sensor network silent interval duration on system use, by transforming the raw occupancy data to include the duration of the silent interval. Unoccupied intervals in the raw data file having a duration of less than or equal to the silent interval are marked as occupied rather than unoccupied, and the new value of assumed occupancy is calculated. Table 3 provides an example, and shows how the application of a three minute silent interval affects the duration of assumed occupancy and system use over a short time series: the transformed data are highlighted in bold type.

In this example, a "1": indicates a sensor network signal indicating occupancy, a "0" indicates no signal from the sensor network, and the space is assumed to be empty. The raw data show 4 minutes occupancy. Applying a 3 minute silent interval replaces each three-minute sensor network silent interval with an occupied signal, thereby increasing the total occupancy to 13 minutes.

Table 3. Raw and transformed occupancy pattern assuming three-minute inactivity switch interval

	Raw Data (Mins)	Three Minute Silent Interval (Mins)
	1	1
	0	**1**
	0	**1**
	0	**1**
	1	1
	1	1
	0	**1**
	0	**1**
	0	**1**
	0	0
	0	0
	1	1
	0	**1**
	0	**1**
	0	**1**
SUM	**4**	**13**

3.2.2 Results

Table 3 shows the cumulative time (in minutes) that each room was occupied, as measured by individual PIR sensors, along with the percentage difference in occupied time between the measurements collected by each detector. Table 3 also shows the cumulative occupied time as determined using a composite signal from the three PIR sensors in each room, and models the effects of 5 minute, 20 minute, and 30 minute sensor network silent intervals on presumed occupancy, based on the sensor network composite signal.

Table 3. Cumulative occupied time (mins) as measured by individual PIR sensors and sensor network over two month monitoring period

Office	PIR1	PIR2	PIR3	Pct Diff(1)	Comp	Comp+5	Comp+20	Comp+30
1	1620	3533	3427	54%	3975	5775	8633	10277
2	156	599	423	74%	725	2096	5490	7581
3	3763	6702	7268	48%	8464	11816	16090	18371
4	3503	6756	8573	59%	9109	11498	14725	16436
5	6018	6408	4365	32%	6773	8625	11614	13354
6	3216	1618	3296	51%	5178	8798	12789	14297
7	4804	4940	3653	26%	6473	9608	12666	14306
8	1058	2603	913	65%	2761	4586	8129	9798
9	7179	6279	6025	16%	9305	12709	16401	18323
10	8462	9005	10794	22%	12419	15716	19488	21440

1. Percent difference was calculated as (max-min)/max

Figure 6 depicts these same data in graphic form. As in the first study, sensor position and aiming were vital for determining whether or not the space was occupied (left panel). Again, also as in the first study, increasing the sensor network silent interval produces significant increases in assumed occupancy (right panel). Since we did not have cameras in each office, we are unable to show the deviation from actual occupancy as in the first study. We are currently collecting data to allow this analysis.

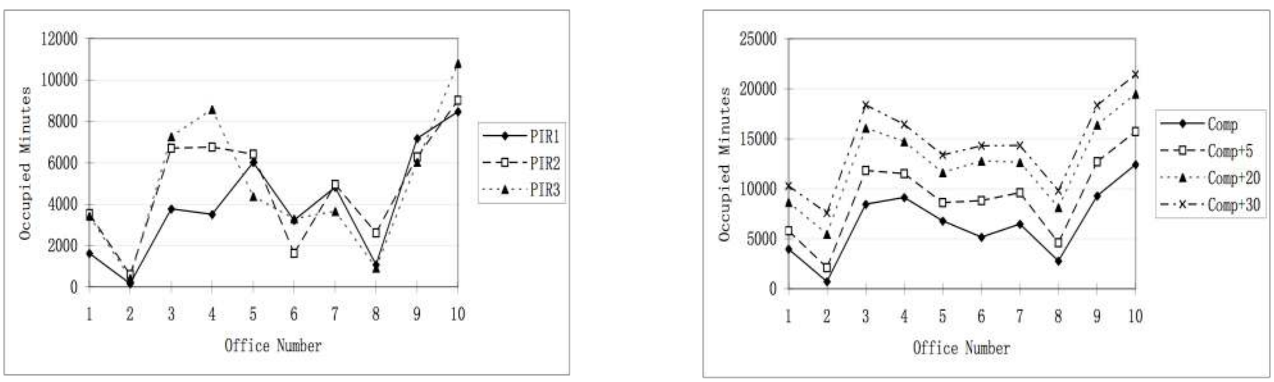

Figure 6: Cumulative occupied time (mins) as measured by PIR sensor network over two month monitoring period

Figure 7 depicts the total number of occupied minutes over the two month monitoring period for all ten offices, using a composite signal from the PIR sensor network. As expected, occupancy was higher during the week than over the weekends, and was lowest over the July 4th statutory holiday. Since some of these data were collected from offices occupied by university faculty during the summer months, occupancy during the week is lower than would be expected in a more traditional office setting. If we assume each office was continuously occupied for six hours every day, the maximum number of occupied minutes per day would have been 3600 minutes. The observed maximum was on June 20th 2005, with a peak of 1760 minutes, slightly under half of the maximum. Once the academic term commenced (right panel), observed occupancy in these offices increased slightly, as expected.

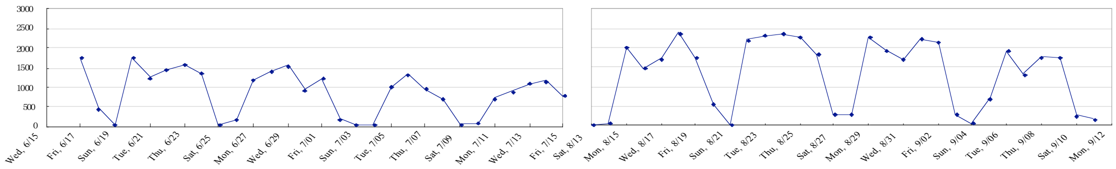

Figure 7: Total occupied minutes per day (10 private offices over 2 months)

Figure 8 depicts the total number of occupied minutes per hour for all ten offices over the two month monitoring period using a composite signal from the PIR sensor network (solid curve), along with the effects of sensor network silent interval duration on hourly occupancy for 5, 20 and 30 minute silent intervals (three curves described by dashed lines).

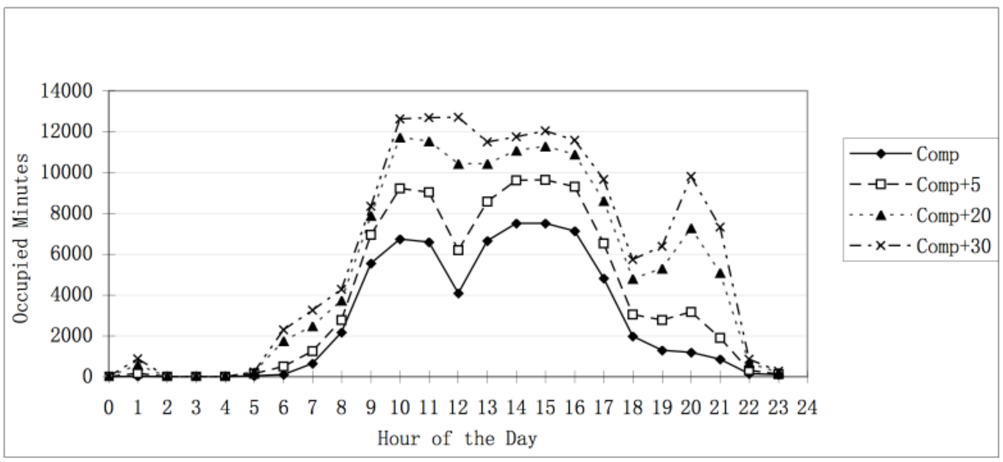

Figure 8: Total occupied minutes per hour (10 private offices over 2 months) and effect on occupied time of sensor network silent interval

3.3 Study III: Sensor Network Firing Rate and Occupancy in an Open-Plan Office

This section reports preliminary results from a currently-ongoing study that investigates the relationship between sensor network pulse rate and occupancy in an open-plan office. A network of sensors provides a more accurate measure of occupancy than a single sensor, and it is also possible that some aspect of the sensor network response to occupancy can be used to differentiate between one or more occupants in a monitored space.

3.3.1 Methods and Procedures

PIR sensors and data acquisition systems were the same as used in the second study, reported above. These systems were installed in a large open-plan office (Figure 9) (dimensions about 10m x 11m) which hosted 23 cubicle workstations: three PIR sensors were mounted in each cubicle workstation. This room is occupied by senior architectural engineering students. The PIR data were complemented by a digital video record of office occupancy. Four AXIS digital video cameras were mounted at ceiling level in the corners of the room. The software controlling each camera recorded the date and time of each image (in date:hour:minute:second format), writing this information clearly in the lower right area of each image frame. A separate image was collected every two seconds, and these separate images were automatically appended to a QuickTime file, which provided a time-lapse movie showing activity in the room. These time-lapse movies were manually reviewed by a human observer, who recorded the maximum number of occupants who were in the room at each minute of the day. This was compared with the number of PIR sensor pulses in each minute.

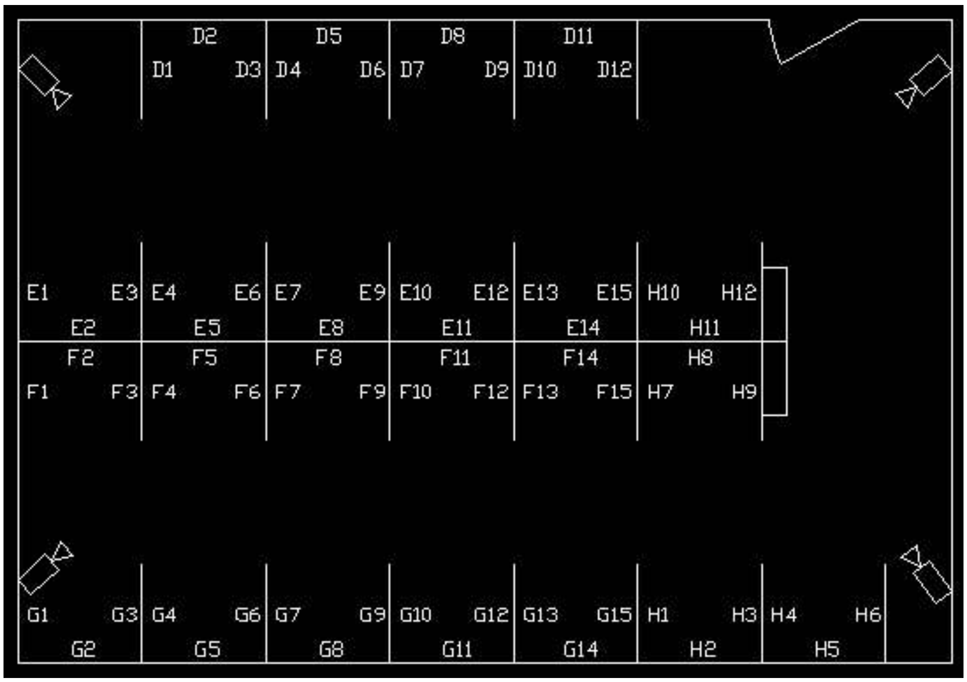

Figure 9: Plan view of open-plan office layout

3.3.2 Results

Since this study is still ongoing, here we report preliminary analysis of data collected from two days. During one of these days the room was lightly occupied, and during the second day the room was more heavily occupied. Figure 10 depicts the relationship between room occupancy and PIR sensor pulse rate over all minutes of the two days portrayed, along with the best-fit linear regression line through the data. Even though the figure depicts data from only two days, it is clear that there is a relationship between the number of occupants in the room and the PIR sensor pulse rate.

The coefficient of determination (r^2) describes the proportion of variance in one variable (the maximum number of occupants in the room in any minute) that can be predicted by the other variable (the maximum number of PIR sensor pulses observed in any one minute). In this case, the coefficient of determination (r^2) is equal to 0.672, which corresponds to a product-moment correlation coefficient (r) of about .815. By convention, product-moment correlation coefficients (r) greater than .8 are described as being strong, while those less than this value are described as being weak. In this instance, about 67 % of the variation in the number of occupants can be accounted for by the PIR sensor pulse rate.

This result is very encouraging. Even though the model relating the two variables is very simple, it shows a clear relationship. Further, it may be possible to increase the predictive power of the model by including other variables.

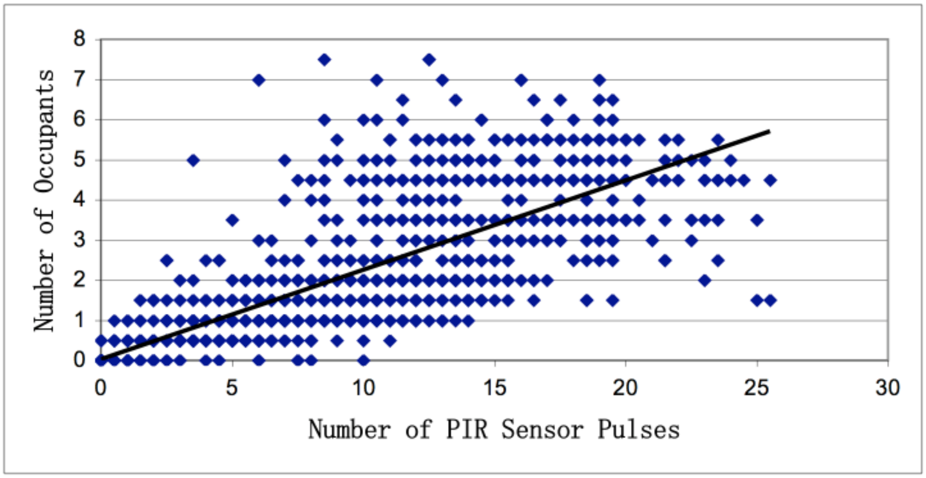

Figure 10: Relationship between PIR sensor pulse rate and occupancy over two days in an open-plan office

4 Conclusions

As we have previously noted, there is a growing literature that addresses the effectiveness of occupancy sensors for controlling office ambient lighting systems, and other studies have evaluated the effectiveness of occupancy-based switching for power management of office equipment (Audin, 1999; Floyd, Parker, McIlvaine & Sherwin, 1995; Jennings, Rubinstein, DiBartolomeo & Blanc, 2000; Mannicia, Burr, Rea & Morrow, 1999; Mannicia, Tweed, Bierman & Von Neida, 2001; Richman, Dittmer & Keller, 1996; Tiller & Newsham, 1993; Todesco & Robillard, 1995; Siminovitch & Page, undated; Von Neida, Mannicia & Tweed, 2001). This work shows that occupancy sensors reliably deliver significant energy and demand savings in infrequently or unpredictably occupied spaces, such as washrooms, stairwells, corridors, storage areas (Todesco & Robillard, 1995), and mail carrier sorting stations (Siminovitch & Page, undated). Comparable savings have eluded general office applications, and occupancy sensors have not achieved as wide use as other energy-saving lighting technologies (Von Neida et al., 2001). There are often large differences between actual observed savings (less than 50% reductions) and industry estimated savings (up to 70% reductions) that result from the application of single point occupancy detection systems.

The results of this work may help explain the performance limitations of currently available systems and suggest opportunities to improve system performance and capabilities. The results reported here establish that more effective indoor environmental control and management requires more extensive sensing than is currently deployed in most buildings, and more extensive analysis of sensor data.

If a single measurement point were sufficient to accurately characterize occupancy in a given space, the occupied time measured by several independent detectors monitoring a space would be about the same. On the other hand, observed differences in the total occupied time measured by several independent detectors suggests that each detector, on it's own, provides a less accurate measure of occupancy than might be obtained using a composite signal from several individual detectors. We have established that a sensor network, consisting of several independent detectors monitoring the same space, provides more accurate determination of occupancy than is possible with a single point of detection.

The second focus of this research relates to the analysis of the data stream produced by the sensor network. We have investigated the application of a class of graphical probability models, called belief networks (Dodier, 1999), for the purposes of prediction, diagnosis, and calculation of the value of information in building control systems (Dodier, Henze, Tiller & Guo, 2005). While this work showed that belief network analysis provides a sophisticated paradigm for determining occupancy from a sensor network, it also showed that the belief network was computationally intensive, and may not be practical for application in this area at this time.

Consequently, we also proposed an alternative control algorithm, which we are still evaluating. This control strategy is based on two parameters, as follows: 1) signals for the sensor network that indicate occupancy, and; 2) the duration and frequency of sensor network silent intervals (time intervals that the space was actually occupied but during which the sensor network indicated it was vacant). A controller based on these two parameters would have at least two advantages relative to current technology and practice. First, the savings from switching off services in unoccupied spaces will be greater, because the sensor network silent interval can be much shorter than an arbitrarily defined interval, and; second, in a real application the duration of the silent interval can be dynamically defined, and change based on the actual occupancy profile of the space and response of the sensor network. In this scenario, the sensor network and controller would "learn" the most appropriate silent interval based on actual system performance, and would most likely develop and apply different operating parameters in different spaces.

The third phase of the project involves the development and implementation of prototype systems in a real building. We therefore conclude this report with a brief discussion of the prospects for such systems, based on the work conducted to date.

Building occupancy information has utility beyond lighting and HVAC system control. A real-time display showing the current sensor network status could be useful for other applications. We have therefore developed a web-based display that portrays the current status of each PIR sensor in a sensor network monitoring building occupancy (Figure 11).

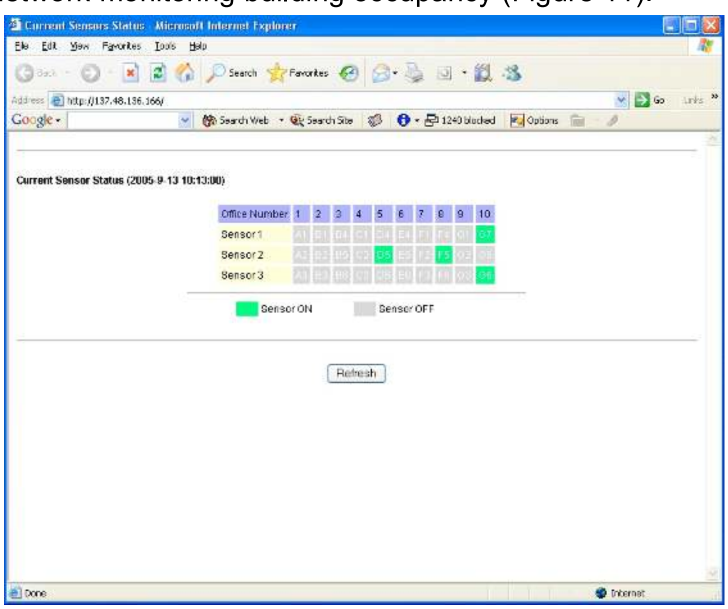

Figure 11: Web page displaying status of PIR sensors located in ten private offices

In the future, we will extend this basic capability by applying probabilistic inference to the data stream, so that the web page displays a probabilistic judgment concerning the likelihood that each monitored office or area is occupied, as a supplement to the status of each sensor. It will also be possible to display time-series graphs showing the occupancy profiles for one or more offices/areas over defined time intervals (e.g., last hour, last day, etc.), provide statistical summaries of the aggregated occupancy profiles, and perhaps even provide an estimate of the number of occupants in different spaces.

Over the course of the project, we have moved to wireless PIR sensors for data acquisition, and a wireless platform would be preferable for product prototyping and development. Although the technologies used here are suitable for data collection in a research context, these technologies have two significant limitations that limit their use in real-world applications. These relate to power requirements, and data communications methods and protocols.

The wireless sensors used here are battery-powered, and the user-defined address of each sensor is lost when the power fails. The communications protocol (X10) used by these devices is relatively unsophisticated. For example, this protocol does not support error checking to verify that a transmitted signal has in fact been received, supports a limited address space, and communication between the sensors and the receiver uses point-to-point transmission.

Several possibilities exist to resolve these limitations. For example, it would be useful to adapt and extend current passive infrared (PIR) occupancy sensing systems to incorporate current wireless communications protocols (e.g., Bluetooh, ZigBee). Point-to-point communications should be replaced by a mesh network model. In a mesh network, individual devices incorporate both sensing and data transmission capabilities. Each device cooperates with all other devices to relay signals to their destination. This method improves the reliability of signal transmission, and can also reduce power requirements, as the distance that signals must travel is significantly reduced.

Power requirements can be met in at least two ways. One possibility involves incorporating a photovoltaic into the sensor circuit as a supplement to the battery. In such a hybrid system, a photovoltaic cell would be connected to a rechargeable battery. During the daytime, the detector would be powered by the photovoltaic cell, which would also charge the battery. During the nighttime, the detector would be powered by the battery. Alternatively, wireless PIR occupancy sensors could be incorporated into ceiling or furniture systems, to ensure a reliable power supply.

5 References

Audin, L. (1999) Occupancy sensors: Promises and pitfalls. *E-Source Tech Update*. TU-93-8. Boulder, CO.

Dodier, R.H. (1999) *Unified prediction and diagnosis in engineering systems by means of distributed belief networks*. Doctoral dissertation, Department of Civil, Environmental and Architectural Engineering, University of Colorado.

Dodier, R., Henze, G.P., Tiller, D.K. & Guo, X. (2005). Building occupancy detection through sensor belief networks. Under review by *Energy and Buildings*. Submitted May 2005.

Floyd, D.B., Parker, D.S., McIlvaine, J.E.R. & Sherwin, J.R. (1995) Energy efficiency technology demonstration project for Florida educational facilities: Occupancy sensors. *FSEC-CR-867-95*. Cocoa FL: Florida Solar Energy Center Building Design Assistance Center.

Jennings, J.D., Rubinstein, F.M., DiBartolomeo, D. & Blanc, S.L. (2000) Comparison of control options in private offices in an advanced lighting controls testbed. *Journal of the Illuminating Engineering Society of North America*, 29, 3960.

Maniccia, D., Burr, R., Rea, M.S. & Morrow, W. (1999) Occupant use of manual lighting controls in private offices. *Journal of the Illuminating Engineering Society of North America*, 28, 4256.

Mannicia, D., Tweed, A., Bierman, A., & Von Neida, B. (2001) The effects of occupancy sensor time-out setting on energy savings, lamp cycling and maintenance costs. *Journal of the Illuminating Engineering Society of North America*, 30, 97 – 110.

Richman, E.E., Dittmer, A.L. & Keller, J.M. (1996) Field analysis of occupancy sensor operation: Parameters affecting lighting energy savings. *Journal of the Illuminating Engineering Society of North America*, 25, 8392.

Siminovitch, M.J. & Page, E. (undated). *U.S. Postal Service Task Lighting Study*. Webpage located at http://eetd.lbl.gov/btp/lsr/projects/postoffice/postmain.htm. Downloaded Sunday June 30th 2002.

Tiller, D.K. & Henze, G.P. (2004). Converging redundant sensor network information for improved building control. Topical Report for Cooperative Agreement DE-FC26-04NT41971: Reporting Period December 1st 2003-November 30th 2004.

Tiller, D.K., Henze, G.P. & Guo, X. (2005). Converging Redundant Sensor Network Information for Improved Building Control. Clima2005 Proceedings, Lausanne Switzerland, (Paper 235s).

Tiller, D.K. & Newsham, G.R. (1993) *Desktop Computers and Energy Consumption: A Study of Current Practice and Potential Energy Savings*. Canadian Electrical Association, Montreal, Canada, Report Number CEA 9101 U 829, April.

Todesco, G. & Robillard, P. (1995) *Unoccupied Spaces and Wasted Lighting Energy*. Canadian Electrical Association, Montreal, Canada, Report Number CEA 9114 U 919, June.

Von, Neida, B., Maniccia, D. & Tweed, A. (2001) An analysis of the energy and cost savings potential of occupancy sensors for commercial lighting systems. *Journal of the Illuminating Engineering Society of North America*, 30, 111 – 125.

6 List of Acronyms and Abbreviations

HVAC	Heating, ventilating, and air-conditioning
PIR	Passive infrared

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