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Lighting System Control in Office Building Using Occupancy Prediction Based on Historical Occupied Ratio

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Lighting System Control in Office Building Using Occupancy Prediction Based on Historical Occupied Ratio

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Abstract. Intelligent control has attracted more attention in the operation of commercial buildings, and the control of lighting system is one significant part. The way of lighting system control in most of commercial buildings is commonly based on occupancy data. The passive infrared (PIR) sensor is mostly chosen to obtain the occupancy data. Compared with the traditional lighting system control method based on constant schedule, the proposed control methods are adjusted by actual occupancy. The problem lies in the inaccuracy of PIR sensor, which causes "false off" when room is still occupied. To solve this problem, the current control method uses delay period as the criteria. In this research, we process the occupancy data, and improve the control method combining occupancy prediction method. The improved prediction method mainly correlates the prediction with historical occupied ratio. Higher accuracy and lower rate of "false off" are achieved.

1. Introduction

Lighting, offered by electric utilities, ranks among the dominating power demand end use and grid-based electric lighting consumption accounts for 19% of the total global electricity production [1]. Significant energy conservation is possible by energy efficiency improvement, and lighting is one of it [2]. Besides LED lighting popularization, intelligent lighting system control also contributes to energy conservation, which attracts more attention these years.

Through comprehensive analysis, automatic lighting control system saves lighting load ranging from 15% to 75%, of which the average performance is 30% [12]. As for the current control method, logic is relatively simple -- judging the state after a period delay [7]. In view of this, Richman [11] studied the impact of different values of delay period on the energy conservation. Maniccia and Von Neida [9] also did the same research. For private office room, energy conservation is 38% to 28%, when the delay period varies from 5 minutes to 20 minutes. For open office area, when the delay period varies from 5 to 20 minutes, the energy conserves from 60% to 17%. Other detailed research is as shown in Table 1. From previous researches, the impact of delay period on energy conservation is important.

However, during the measurement and evaluation of lighting control, one inevitable problem is that the lighting system is frequently turned off by mistake, even if the room still occupied. To deeply study the performance of sensor, the occupancy tends to be underestimated if single sensor is used, sometimes as low as 80% [6].

Actually, the control error is related to the limited sensing precision. The sensing range of PIR is shown in Figure 1 [3], which infers that as the range of movements decreases, the detectable range of

motion sensor also shrinks. As for the movement with whole body, the detectable range for PIR sensor is 12 meters, while as for the movement with upper body or only arms, the range of detection shrinks down to 6 meters.

Therefore, in terms of lighting system control, besides the energy consumption, the comfort of people also matters. Based on the current method, this article proposes the model predictive control, which based on occupancy prediction to avoid frequent "false off" [10].

Table 1. Summary of previous studies

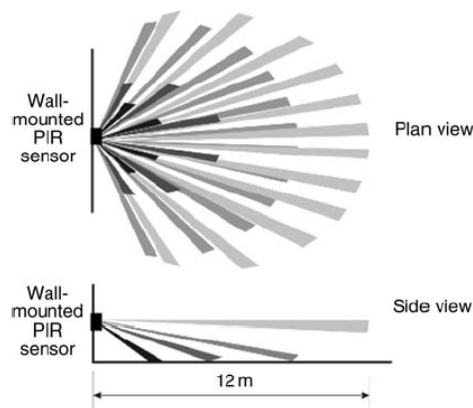| Source	Lighting system energy savings	Time delay [10]
[11], 1996	3-50%	5-20 min
[5], 1996	10-19%	7-15 min
[9], 2001	43%	30 min
[13], 2001	28-38%	5-20 min
[8], 2000	20-26%	15-20 min
[4], 2001	6.9-33.3%	5-20 min

Figure 1. Illustration of precision and valid coverage of PIR sensor

2. Methodology

As for the lighting system control, the interaction relationship lies among occupants, sensors, controllers and lighting system, which is illustrated in Figure 2. If there is occupant in the room, the PIR sensor senses the movement, records the occupancy data and transmits data to controller. The controller will process the occupancy data and normally, save the occupancy data. On the other hand, the operation and status of the lighting system impact occupants. If lighting system is turned off when room occupied, occupant may wave hands to restart the lighting system. This is called the feedback.

From Figure 2, the loop relationship of control is illustrated. In the process of the lighting control, the reason for the lighting system "false off", is that the occupancy data from PIR sensor deviates from the real occupancy data. Hence, on one hand, the occupancy from PIR sensor should be analyzed and revised. On the other hand, the control algorithm can be improved to enhance the control accuracy and avoid lighting system being turned off by mistake.

The methodology of the research is illustrated in Figure 3. There are mainly three types of data in the research. 1) Real occupancy data, 2) Occupancy data from PIR sensor, 3) Predicted occupancy data.

Real occupancy data refers to the true occupancy state, which can be used to validate the model and control algorithm. Occupancy data from PIR refers to occupancy state from the PIR sensor. Predicted occupancy data refers to the data used for control. The occupancy from PIR and real occupancy data

are combined to analyze the data quality of the sensor. The predicted occupancy data and real occupancy data are combined to validate and evaluate the control algorithm.
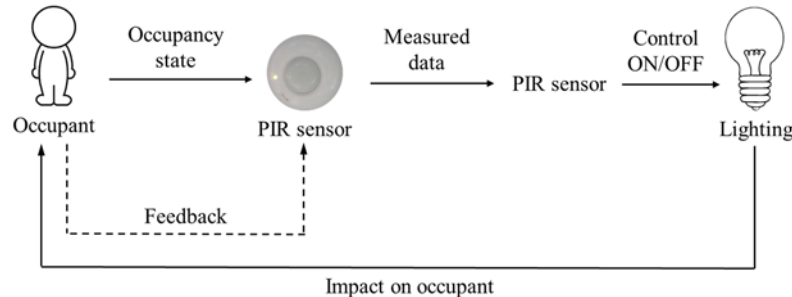

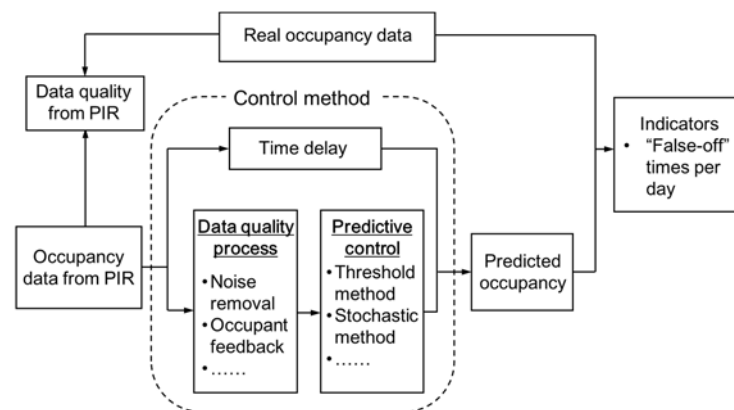**Figure 2.** Physical relationship during lighting system control

Figure 3. Methodology map of the occupancy model predictive lighting control

3. Data process

To avoid the huge accuracy discrepancy among PIR sensors, we conduct the preliminary experiment to analyze PIR data quality. The confusion matrix represents the accuracy of the present PIR sensor.

Figure 4 shows the comparison of real occupancy and the occupancy from PIR sensor. In the figure, the measurement duration is 1 hour, however, the PIR sensor continually reports the room to be unoccupied, even if there is continuously occupants in the room.

We propose two duration definitions to characterize the occupancy data from PIR, and use the statistical analysis to preprocess the PIR occupancy. Figure 5 illustrates the two duration definitions: duration of occupied time from PIR sensor (a) and duration of unoccupied time from PIR (b).

Table 2. Confusion matrix result of present PIR sensor

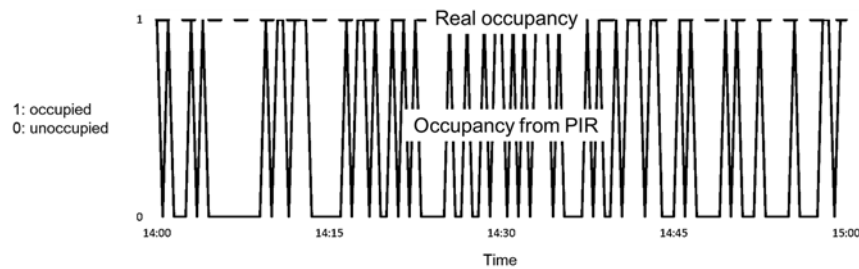|	Occupied actually	Unoccupied actually
Occupied from PIR	15.5%	1.6%
Unoccupied from PIR	16.5%	66.4%

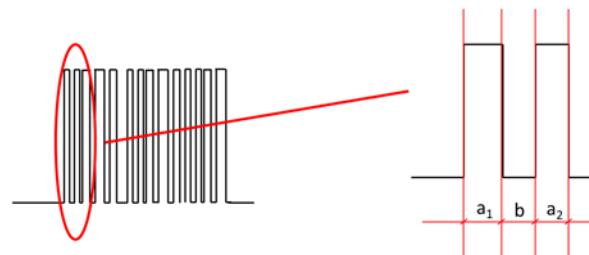**Figure 4.** Comparison of real occupancy data and data from PIR

Figure 5. Duration definitions during PIR occupancy data process: (a) duration of occupied time from PIR, (b) duration of unoccupied time from PIR

We make statistics about the cumulative distribution of the two types of duration, which are extracted from PIR occupancy data. The duration of occupied and unoccupied state tends to be less than 3 minutes, which is unusually small for regular office. Therefore, in the processing, we assume that the lighting system is unnecessarily turned off if the room is unoccupied for less than 5 minutes.

Besides the data preprocess, during the practical control, the feedback from occupants also helps with the real-time data amendment. When "false-off" occurs, occupants will react immediately to turn on the lighting system again. The algorithm is that if the lighting system is off in the previous time step and turned on in the directly next time step, then "false off" is considered to occur and the historical occupancy data will be revised. The revised occupancy data will be utilized to predict occupancy in the future.

4. Control method

In this research, three control methods are focused and compared. The first one is traditional time delay method. The other two methods are based on occupancy model prediction. If the room is detected unoccupied, the prediction will be performed to judge whether to turn off the lighting system in the next time period. The two prediction control methods are threshold method and stochastic method.

4.1. Time delay method

The time delay method delays the turn-off operation until the room is detected to be unoccupied for a certain period. From the literature review, the delay period varies from 5 minutes to 30 minutes. In the research, we set the delay period as 5 minutes.
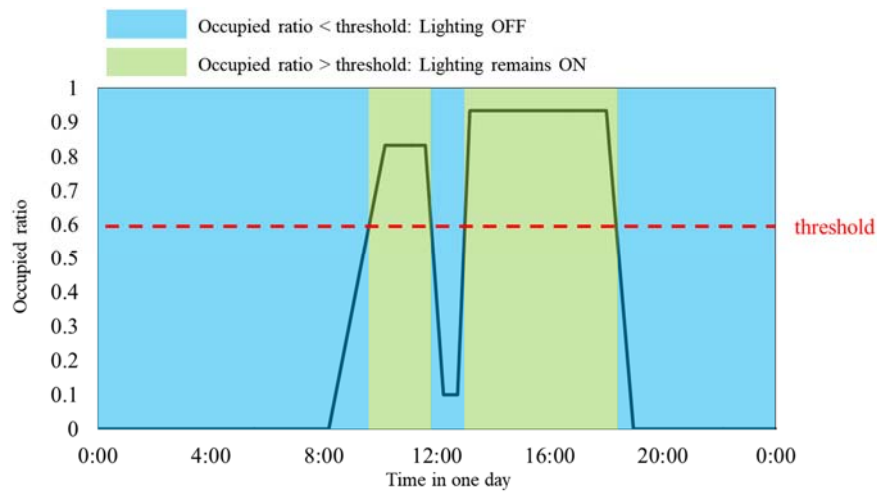
Figure 6. Illustration of threshold control method. The historical occupied ratio is to compare with threshold, if the occupied ratio < threshold, the lighting system will be turned off, in contrast, the lighting system will remain on.
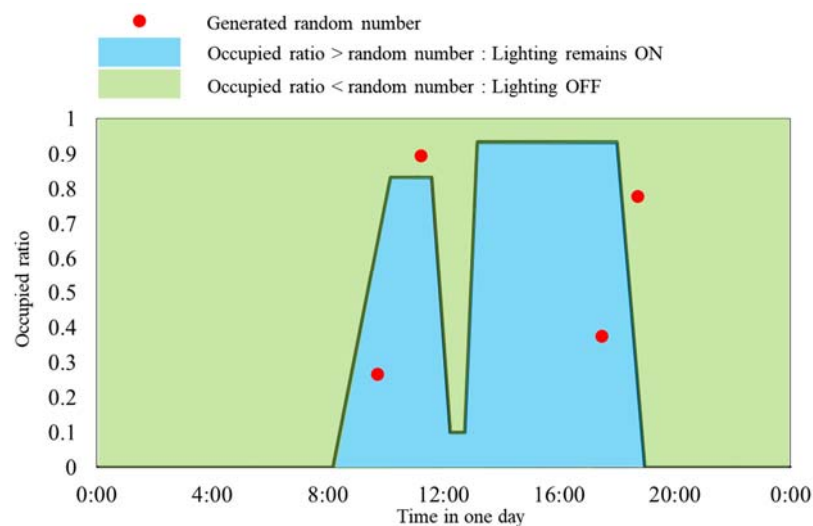

Figure 7. Illustration of stochastic control method. The historical occupied ratio is to compare with a random number, if the occupied ratio < random number, the lighting system will be turned off, in contrast, the lighting system will remain on.

4.2. Threshold method

Threshold method is based on the room historical occupancy ratio. Figure 6 shows the judgement principle of threshold method. Just like the delay period of time delay method, the threshold is preset and adjustable. During the control, if the PIR sensor detects the room to be unoccupied, occupancy prediction will be performed to judge whether to turn off the light. The criteria is historical occupied ratio and threshold value. If the historical occupied ratio is less than the threshold, then at this time step, the room is presumed to probably be unoccupied, and the lighting system shall be turned off. If the historical occupied ratio is larger than the threshold, then at this time step, the room is presumed to probably be occupied, and the lighting system shall remain on state. And the occupancy data of this time step will be revised and recorded as occupied.

4.3. Stochastic method

Stochastic method is also based on the room historical occupancy ratio. Figure 7 shows the judgement principle of stochastic method. The difference between stochastic and threshold method lies in the comparison criteria. For stochastic method, the comparison criteria is rather than a stable threshold value, but generated random number at each time. During the control, if the PIR sensor detects the room to be unoccupied, one random number will be generated. To compare the random number and the occupied ratio, if the historical occupied ratio is less than the random number, then at this time step, the room is probably unoccupied, and the lighting system will be turned off. If the historical occupied ratio is larger than the random number, then the room is more likely occupied, and the lighting system shall remain on. And the occupancy data will be revised accordingly.

5. Results

Lighting system control in an office room is taken as the case study. This office room supplies working conditions for three occupants, who are office stuffs with regular working routine. The room is around 20 m^2, and there is no workstation partition in the room. One PIR sensor is installed on the ceiling. The processed data is in the temporal resolution of 30 seconds. The data recorded from November 1, 2017 to December 1, 2017 is utilized to establish the historical occupancy database. After data preprocessing, the historical occupied ratio is calculated and illustrated in figure 8. The historical occupied ratio depicts the working characteristic of this office room, and contributes to the occupancy prediction for lighting system control.

The control performance results come from the control of 30 weekdays (Figure 9). The control methods include (1) traditional time delay method; (2) threshold method; (3) stochastic method. The true value is the real occupancy in the office, and the lighting system is assumed to operate as fixed schedule. "Total duration", Times of "turn-on" and Times of "false-off" are selected as the evaluation indicators. The results are summarized in Table 3.

As for the total duration of lighting system, the fixed schedule of lighting operation consumes more energy, for the lighting system is turned off only out of working period. The three control methods achieve energy conservation by shrinking the total duration

of lighting system, and that of threshold method is the shortest.

As for the times of "turn on", the two new proposed methods outperform the traditional time delay method. The indicator of times of "false off" directly relates to the comfort of occupants. Compared with the traditional method, the proposed prediction control methods decrease the times of "false off" and enhance the control performance.

Table 3. Evaluation indicator comparison

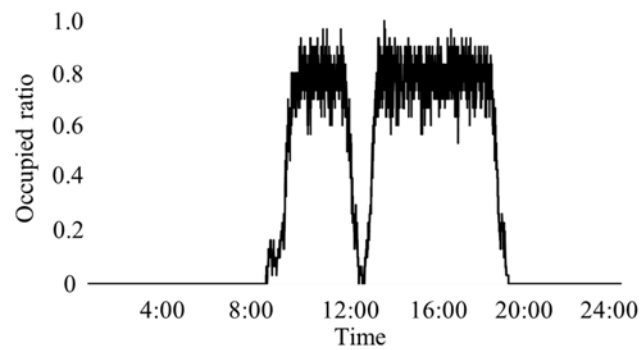| Method	Total duration (h/day)	Times of "turn-on" (times/day)	Times of "false-off" (times/day)
True value	10.3	/	/
Time delay method	9.0	14.8	4.7
Threshold method	8.8	8.5	1.3
Stochastic method	9.1	8.8	1.3

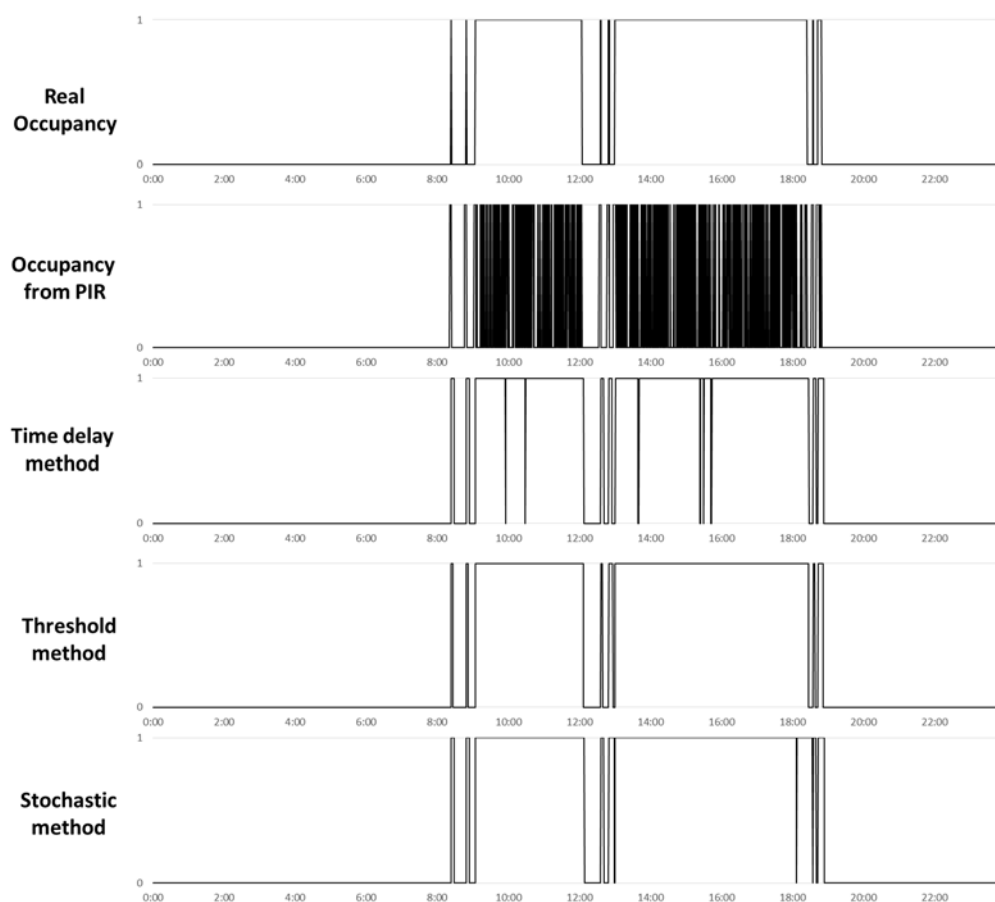**Figure 8.** Historical occupied ratio from case study

Figure 9. Comparison of control result in one day

6. Discussion and conclusion

As for the methods and the results, this research focuses on the occupancy prediction for model predictive control and takes lighting system control as one case study. Prediction results directly and immediately affects the occupants in the building, so the feedback from occupants in turn instructs the control and helps with data revision.

In the proposed prediction method, the occupancy state for the predicting time step is related to the historical occupied ratio. The amount of selected history days to calculate the ratio may affect the control performance. The occupant behavior and occupancy schedule may follow certain routine,

which can be characterized. However, the routine may change gradually. So for further research, the update of the occupied ratio and weight for history days should be considered to enhance the control performance.

This research mainly devotes to eliminating the discomfort of occupants during lighting control. The most effective way to control the lighting system with higher comfort is to enhance more accurate occupancy prediction in the room. The proposed method now relies on the occupied ratio, for other methods to research in the future, the prediction may rely on the previous occupied state for several time steps. The prediction window matters a lot, which varies from 5 minutes, 1 hour even to 1 day or 1 week. There is plenty of work to study in this field.

References

[1]   IEA. 2006. Light's labour's lost: policies for energy-efficient lighting.

[2]   IEA. 2017. Energy Efficiency 2017. https://www.iea.org/efficiency/.

[3]   BENYA, J. 2001. Advanced lighting guidelines, New Buildings Institute, Incorporated.

[4]   CHUNG, T. & BURNETT, J. 2001. On the prediction of lighting energy savings achieved by occupancy sensors. Energy engineering, 98, 6-23.

[5]   FLOYD, D. B., PARKER, D. S. & SHERWIN, J. R. 1996. Measured Field Performance and Energy Savings of Occupancy Sensors: Three Case Studies.

[6]   GUO, X. 2007. Occupancy sensor networks for improved lighting system control, The University of Nebraska-Lincoln.

[7]   GUO, X., TILLER, D., HENZE, G. & WATERS, C. 2010. The performance of occupancy-based lighting control systems: A review. Lighting Research & Technology, 42, 415-431.

[8]   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, 29, 39-60.

[9]   MANICCIA, D., TWEED, A., BIERMAN, A. & VON NEIDA, B. 2001. The effects of changing occupancy sensor time-out setting on energy savings, lamp cycling and maintenance costs. Journal of the Illuminating Engineering Society, 30, 97-110.

[10]   MIRAKHORLI, A. & DONG, B. 2016. Occupancy behavior based model predictive control for building indoor climate—A critical review. Energy and Buildings, 129, 499-513.

[11]   RICHMAN, E., DITTMER, A. & KELLER, J. 1996. Field analysis of occupancy sensor operation: parameters affecting lighting energy savings. Journal of the Illuminating Engineering Society, 25, 83-92.

[12]   RUNDQUIST, R. A., MCDOUGALL, T. G., BENYA, J., MCCAFFREY, E. M., TORRERO, E. A. & JOHNSON, K. F. 1996. Lighting controls: Patterns for design.

[13]   VON NEIDA, B., MANICRIA, 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, 30, 111-125.