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A review on sensing-based strategies of interior lighting control system and their performance in commercial buildings

Khairul Rijal Wagiman[1], Mohd Noor Abdullah[2], Mohammad Yusri Hassan[3],
Nur Hanis Mohammad Radzi[4]

[1]Industrial Training Institute, Malaysia
[1,2,4] Green and Sustainable Energy Focus Group (GSEnergy), Faculty of Electrical and Electronic Engineering,
Universiti Tun Hussein Onn Malaysia (UTHM), Malaysia
[3]Centre of Electrical Energy Systems (CEES), School of Electrical Engineering, Faculty of Engineering,
Universiti Teknologi Malaysia (UTM), Malaysia

Article Info

ABSTRACT

Artificial lighting consumed significant amount of electrical energy in commercial buildings. Therefore, intelligent control strategies are widely implemented to reduce the lighting energy consumption. This paper presents comprehensive review of the current sensing-based strategies (i.e. occupancy, daylight and mixed), sensors placement methods (i.e. occupancy and light) and factors affecting the performance of the lighting control strategies. Based on literature survey, the sensors placement methods can be categorized into three approaches: fixed, mathematical equation and optimization. The state-of-the-art of these approaches are discusses in details. It found that, the optimization-based approach capable to find the optimal sensor placement (numbers and positions) effectively. Moreover, the mixed strategy can be produced the highest energy savings up to 95% compared with other strategies. The occupancy pattern and building characteristics are the main factors to contribute higher energy savings of sensing-based strategies in commercial buildings.

Corresponding Author:

Mohd Noor Abdullah,
Green and Sustainable Energy Focus Group (GSEnergy),
Faculty of Electrical and Electronic Engineering,
Universiti Tun Hussein Onn Malaysia,
86400, Batu Pahat, Johor, Malaysia.
Email: mnoor@uthm.edu.my

1.   INTRODUCTION

The lighting system is one of the main systems in the buildings and it has consumed around 17% of the total electric energy [1]. Based on this fact, the energy consumption needs to be reduced for economic and environmental benefits. There are several strategies can be considered: converting low energy efficient lamp technologies to high energy efficient lamp technologies, such as light emitting diode (LED) [2], occupancy-based control and daylight-based control [3] and scheduling-based control [4]. In literature, LED lamp technology has a prominent energy efficient lamp among other lamp technologies due to its special characteristic: high color temperature and efficacy as well as less power consumption [5, 6]. Moreover, LED has great control performances: easy to control and its output power is directly proportional to dimming level [7]. For occupancy and daylight control strategies, sensors are the main inputs of the lighting control systems. In the occupancy-based strategy, occupancy sensors (e.g. motion sensor) are used to detect the

occupancy status (occupied or un-occupied). The comprehensive review related to occupancy-based strategy in office buildings can be found in [7]. In the daylight-based strategy, the light sensors are used to measure the level of illumination in the room and its unit in lux (lx). The daylight metrics, performance assessment and simulation tools were extensively reviewed in [8]. In the scheduling-based strategy, the timers are used to set the operational time based on work areas or necessities. This strategy was reviewed in [4].

In order to improve the performance of the control strategy, the main inputs of the controller (i.e. sensors) need to be placed with optimum numbers and locations. Apart from improve the performance of the control strategy, reducing investment costs include purchasing and installation can be achieved. Several methods have been proposed by sensor manufacturers and literature for determining the numbers and positions of the sensors (occupancy and light). However, each proposed method has limitation.

In this paper, control strategies related to the sensing-based, which are occupancy and daylight based strategies are reviewed. The review includes sensor technologies, sensor placement methods and energy performance evaluation. Moreover, recommendation for future improvements of the existing strategies are highlighted.

2. SENSING-BASED STRATEGIES

Sensors represent an indispensable element in intelligent and smart systems such as building energy system (BES). In lighting systems, there are two common input devices, namely occupancy and light sensors. The occupancy sensor senses the motion of occupants. Meanwhile, the light sensor senses the light from both the daylight and the artificial light. Then, both types of sensors send the signals to the controller. In sensing-based, there are three popular strategies in the literature are occupancy, daylight and mixed (occupancy and daylight) [8].

2.1. Occupancy-based

Occupants' feedback information is crucial in order to implement control strategies and analyse the performance of the buildings in terms of pattern of energy used, location of occupants and occupants' behaviour. The information gathering can be realized in several ways, namely survey, experiments, simulations and combinations of these ways [9]. However, in most literature, they focused on using sensing technologies (i.e. experiments, simulations and both methods) to acquire occupants' information. In fact, manual switch on/off can significantly contributes the highest reduction of energy consumption compared to the occupancy sensing based in office buildings [10]. However, the main obstacle is the attitudes of the occupants to manually switched off the switch when their leave the room. For this reason, the automatic lighting control system is the way to mitigate the wasted energy from the lighting system in the buildings.

According to [11], occupancy-based control design can be divided into five categories: spatial level, occupancy detection technique, intelligence level, illuminance settings, and time delay setting. However, from literature survey, the occupancy detection technique and illuminance settings have been widely considered in the lighting control strategies. The occupancy detection technique is a motion detection using occupancy sensors which considers on and off signals to be sent to the controller. For the illuminance settings are values of illuminance set by occupants with two states, for example, 500 lux for occupancy and 0 lux for un-occupancy. In [12, 13], they utilized other states which are 500 lux and 300 lux for occupancy and un-occupancy, respectively with accordance to the European Standard EN12464-1. Another work in [14], the illuminance level set-point was considered of 400 lux for occupied and 100 lux for unoccupied in an office room.

Several sensor technologies have been utilized in the literature, including passive infrared (PIR), radio frequency identification (RFID) and WiFi-based. The passive infrared (PIR) sensor is commonly used in this method due to its cost-effective, low power consumption and easy to configure (i.e. binary output). The luminaires will automatically on when the PIR sensor detects the variation of radiation emitted by occupants within field of view (FoV) of the sensor. However, significant drawbacks of the sensor are unable to detect stationary of occupant and needs motion continuously by occupants based on concept of line of sight (i.e. between the occupants and sensor within sensor's FoV) to work properly. Moreover, the sensor is unable to make counting, tracking and identifying the exactly location of occupants within sensor's FoV due to its output [15].

The RFID technology is growing and is widely applied in different range of field, including in sensing system. The RFID uses radio frequency wave in its communication range with their tag. The occupants require the RFID tag to link within the lighting control systems. The advantages of the RFID are they can trace and track the location and density of the occupants based on the distance from the reader to the tags. For application instance, the combination of PIR sensor and RFID sensor were used in lighting control strategy [16].

WiFi-based is the latest technology in the occupancy sensing for lighting system in the building. This technology has been widely used as it is easy to be implemented with the existing network infrastructure. The technology uses mobile devices (MDs) to collect the occupant's information (i.e. occupied or un-occupied, position and number) and it is connected to the wireless network in the buildings [17, 18]. The advantages of WiFi-based application are similar to RFID sensor, but the location of the occupants can be detected accurately [19, 20].

2.2. Daylight-based

Daylight harvesting is crucial to reduce depending on fully utilization of artificial light during daytime. Consequently, it can reduce electrical energy consumption of lighting in the buildings. One of the important factors in building design and lighting control strategy is daylighting as specified in the EN12464-1. Daylighting is lighting for an indoor space with openings such as windows that allow daylight into the building and measured in lux, thus it is called as daylight illuminance. Daylight illuminance is the most widely used parameter for lighting design due to the illuminance level directly measures using lux meter or daylighting simulation tools on workspace plane. The light sensor also measures the daylight illuminance as an input parameter of the controller in the buildings. This is a main strategy of sensing-based as it contributes large portion of energy savings in the buildings [8]. In order to evaluate the performance of the strategy, experimental and simulation based studies can be carried out. Most of the researchers have conducted simulation-based due to its fast and reliable of the analysis results. Several daylight simulation tools have been commonly used by the researchers and the designers, such as Daysim, DIALux and Radiance. The simulation tools provide essential data for the analysis, which is different type of sky conditions (e.g. clear, average and overcast conditions) with different time and locations.

2.3. Mixed (Occupancy and daylight)

The uses of mixed sensing method can be benefited to maximize energy performance and satisfy the occupants' preference in the buildings. Williams et al. [8] revealed that this method is the third strategy interested by the researchers in lighting control strategy in buildings and it contributed the highest energy savings among other sensing-based strategies. This method becomes prominent among researchers with current lighting system technologies, which is luminaire with equipped light and occupancy sensors and promising superior energy performance.

3. SENSORS PLACEMENT METHODS

Placement of the sensor is crucial at the design stage of the lighting system in the buildings. At this stage, three sensor placement parameters need to be considered: (1) field of view (FoV) [21, 22], (2) number [21, 23, 24] and (3) position [11, 23, 25, 26]. The FoV value can be determined by referring to the sensor datasheet which is provided by sensor manufacturers and the value is in degree (^{O}). In order to reduce the number of sensors to be installed, the FoV of each sensor cannot be intersected among each other. The number of the sensors to be placed is reflected to the cost to be invested. This means, the optimum number of the sensor to be installed is promising the optimal cost of purchasing the sensors. Apart from the effect of the cost, the higher number of the sensors can also increase the complexity of the control system and consequently, reduce its performance, such as higher computational time and power consumption. According to the reviews conducted, the sensor placement strategy can be categorized into three: (1) fixed, (2) mathematical equation and (3) optimization. In light sensor placement, appropriate sensor position and control zone are the main factors to achieved better energy performance as proved in [27].

3.1. Occupancy sensor placement

The literature showed that majority researchers considered the placement of the occupancy sensor (i.e. PIR sensor) co-located with the luminaire [12, 13, 28, 29] has been employed in the first strategy. Meanwhile, in the second strategy, linear equation with respect to the mounting height and radius of the FoV was used in [30]. In the last strategy, the optimization based methods were used to find the optimal position of the occupancy sensors in the buildings. Wang et al. [21] proposed an improved adaptive binary particle swarm optimization (IABPSO) for optimal strategy for the deployment of sensor in building based on FoV of the sensor. In this study, the working plane was divided into some grids and its grid size depends on the specific application and parameters. The location information of the sensor was based on binary, which is 1 is for sensor placed at the centre of the grid or else it is 0. This information was considered into problem formulation. The proposed method was compared to the standard binary particle swarm optimization (SBPSO) through experimental study and it showed that the proposed method was outperformed than SBPSO in terms of optimal solution and convergence rate.

3.2. Light sensor placement

In the first strategy, the recent LED lighting technology provides the sensor which is equipped with the luminaire. The benefits of this technology are to integrate input and output in one module for the lighting control system as well as to reduce the complexity of the electrical wiring of artificial lighting system. The strategy is the most popular strategy among the researchers [13, 31–34] due to its benefits. However, this strategy is not promising better performance of the control system and not cost effective. In the second strategy, the sensor placement guides which is referred from the manufacturers [30, 35, 36] and daylight performance metrics [37] are the most commonly used, which are derived from mathematical equations. In [35, 36], they provided guidelines to place the light sensor at the appropriate location based on effective window height. In another guideline [30], they provided mathematical equation to calculate the minimum distance of light sensor to window by considering two parameters: mounting height of the sensor to floor and the detection angle of the sensor. However, these methods did not provide the optimal numbers and location of the sensors. Wang et al. [37] proposed lighting system design based on wireless light sensor placement in industrial buildings. In this study, daylight factor (DF) was considered as the measurement parameter and to determine the numbers and locations of the sensor to be placed, the highest calculated DF values were chosen. The experimental results showed that the proposed method had determined the numbers and locations of the sensor and provided energy savings. Nevertheless, the proposed method provided some possible locations (i.e. same values of DFs), which is difficult to make decision to determine the optimum locations of the sensors.

In order to address the shortcomings of the previous strategies, the third strategy has been proposed, which is optimization based [22–24]. Gao et al. [23] introduced lighting control strategy based on optimal placement of light sensor by considering illuminance matrix (I-matrix) by using artificial neural network (ANN) and genetic algorithm (GA). In the research, radial basis function neural network (RBFNN) was chosen to predict the illuminance levels for each location on the working plane across the meeting room. GA was utilized to determine the optimal numbers and locations of light sensors based on the minimum value of root mean square error (RMSE) of standard and predicted of illuminance values. The experimental results showed that the proposed method had determined the numbers and positions of light sensors optimally and showed more accuracy of 60% than conventional methods. However, the daylight harvesting did not consider in their analysis. In recent work [24], they also used combination of ANN-GA to find the best light sensor position by considering daylight at an educational building. The ANN model was utilized to predict the indoor illuminance levels on working plane based on four fixed sensor positions (i.e. two are on the ceiling and two are on the wall). In this research, The ANN inputs represent illuminance values from sensors, output power of the luminaires, horizontal global irradiation, solar elevation and azimuth. The trained ANN data was gathered from the real sensors on the ceiling and the measurement on the working plane using lux meter. The GA was used as optimizer to find the optimal epoch number with different ANN models. The results showed that the best light sensor position was on the ceiling by having the lower error.

Another method, Doulos et al. [22] analysed the optimum position and field of view (FoV) of light sensors by considering daylight harvesting using ELimination Et Choix Traduisant la REalité (ELECTRE). Three criteria were considered, namely coefficient of determination (R^2) of the illuminance levels between the ceiling and the workspace plane, energy savings and illuminance level preference. In this study, both simulation and experimental studies were conducted to compare and validate the results. The analysis was carried out based on two combined scenarios, which are three different positions (i.e. 17.8, 26.7 and 35.8 cm distance from window) and FoVs (i.e. wide, medium and narrow) of light sensors. The results showed that the best position and FoV of the light sensors were 26.7 cm and medium, respectively while satisfying all three criteria. The summary of the related works that focused on sensor placement is illustrated in Table 1.

Table 1. Summary of the related works that focused on sensor placement

Reference	Type of sensor			Strategy		Computational method
	O[a]	L[b]	F[c]	M[d]	P[e]	
[13, 28, 29]	√		√			-
[30]	√			√		Mathematical formula
[21]	√				√	IABPSO
[31]–[34]		√	√			-
[30, 35, 36]		√		√		Mathematical formula
[37]		√		√		DF
[23]		√			√	ANN-GA
[24]		√			√	ANN-GA
[22]		√			√	ELECTRE

Note:
[a] Occupancy, [b] Light, [c] Fixed, [d] Mathematical, [e] Optimization

4.   ENERGY PERFORMANCE OF SENSING-BASED

To evaluate the performance of the sensing-based strategies, energy savings reported from literature has been used. The energy savings from sensing-based strategies are summarized in the Table 2. The influence factors of energy performance are also highlighted. For occupancy-based sensing, it can be seen in Table 2, the highest energy savings recorded was 75% under field measurement study on the office. Whereas, the lowest energy savings recorded was 25% based on a field measurement study on the laboratory. For daylight-based sensing, based on Table 2, the highest energy savings recorded was 81% based on a real field measurement study of the educational building. Whereas, the lowest energy savings recorded was 9% based on a field measurement study of the educational building. For mixed strategies, according to Table 2, the highest energy savings recorded under was 95% based on simulation study on the office room. Whereas, the lowest energy savings recorded was 33% based on a field measurement study on the waiting room of the hospital.

Table 2. Summary of energy savings from sensing-based strategies

Reference	Control strategy[a]	Type of study[b]	Case study	Energy savings[c] (%)
[8]	o	Combined	Commercial buildings	30
	d			41
	od			45
[38]	o	Simulation	Commercial buildings	66
		Real		41
	d	Simulation		68
		Real		43
	od	Combined		49
[39]	o	Real	Small office	75
	d			79
[40]	o	Real	Office	46
			Laboratory	25
	d	Real	Small office	30
			Large office	31
			Seminar room	76
	od	Simulation	Office	55
			Hospital waiting room	33
[41]	o	Real	Large commercial building	27
	d	Real		26
[42]	d	Real	Office	36
		Simulation		56
[43]	d	Real	Office	37
[44]	o	Simulation	Small offices	94
	od			95
[45]	d	Simulation (Relux)	Educational building	35
		Real		40
		Simulation (Daysim)		46
[46]	od	Simulation	Office	70
[47]	d	Real	Educational building (atrium corridor)	45
[48]	d	Real	Educational building	81
[49]	o	Real	Educational building (office rooms)	40
	d			9
	od			48

Note:
[a] o is occupancy-based, d is daylight-based and od is mixed (occupancy and daylight)
[b] Real is including field measurement and experimental studies and Combined is combination of real and simulation studies
[c] The average value

4.1.   Factors affecting the performance of the strategies

Generally, various factors influence the performance of energy in the buildings, including building and lighting system designs (e.g. lighting power density and artificial lighting technology) [49]. Specifically, for occupancy sensing-based, the main factors that influent the energy savings is the occupancy patterns, including office policy, special absences and absence type [50]. Other main factors involved: time delay [51] and sensitivity, positioning and detection area of the sensor [4].

In fact, the factors affecting of daylight sensing-based are building orientation and location, window characteristics, shading devices, reflectance of inner surfaces, partition height and room geometry [52]. In [8], they mentioned that the factors affecting are sky conditions and weather, numbers and location of the sensors, type of use and occupancy. Apart from the abovementioned, the design illuminance level is also one of the main factors of these as results finding in [2, 47, 48].

5. CONCLUSION

This paper provides comprehensive review of lighting control strategies including the current sensing-based strategies, sensor placement method and energy performance of different strategies. In sensing-based, three strategies have been critically reviewed including occupancy, daylight and mixed of occupancy and daylight. These strategies involved sensors to collect and provide the information for the controller for further actions. The sensor placement is crucial to determine the performance of the control system (i.e. dimming levels of luminaires). Most studies considered the luminaires which were equipped with the sensors in order to reduce the complexity of electric circuitry of lighting. However, this method faced higher initial cost and had affected the controller performance, such as higher computational time and less accuracy (i.e. to find the optimum dimming levels of luminaires). Other sensor placement method is used mathematical equations provided by sensor manufacturers. However, the drawbacks of this method are the numbers and positions of the sensors are not place optimally. To address the shortcomings of abovementioned methods, the optimization-based method (e.g. ANN-GA) seems to be the best solution. In light sensor application, the method could determine optimal numbers and locations of the sensors and improved the performance of the control systems (e.g. less energy consumption) consequently, reduce electricity cost and increase life span of the luminaires. However, it required further improvement by considering the daylight and the optimal positions of the sensors. In order to demonstrate the potential to reduce the energy consumption of the lighting system in the commercial buildings, the energy performance results had been illustrated with significant percentage of energy savings. It found that the mixed strategy achieved the highest energy savings compared to the other strategies.

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BIOGRAPHIES OF AUTHORS

Khairul Rijal Wagiman is a Lecturer at the Industrial Training Institute, Selandar, Melaka, Malaysia. He received the B.Eng and M.Eng. in Electrical Engineering from the Universiti Teknologi Malaysia (UTM), Johor Bahru, Malaysia, in 2013 and 2016, respectively. He is currently pursuing the Ph.D. in Electrical Engineering at the Universiti Tun Hussein Onn Malaysia (UTHM), Batu Pahat, Johor. His current research interests include lighting systems design, intelligent lighting control system and control and optimization methods of lighting systems.

Mohd Noor Abdullah received his B.Eng. (Hons) in Electrical Engineering and M. Eng. in Electrical Engineering (Power System) from Universiti Teknologi Malaysia (UTM) in 2008 and 2010 respectively. He also received a Ph.D degree in Electrical Engineering from University of Malaya (UM) in 2014. He has been with Universiti Tun Hussein Onn Malaysia (UTHM) from 2008 to 2014 as a tutor. He is currently as a Lecturer in Department of Electrical Power Engineering, Faculty of Electrical and Electronic Engineering (FKEE), Universiti Tun Hussein Onn Malaysia (UTHM). He also appointed as a head of Green and Sustainable Energy (GSEnergy) Focus Group in FKEE, UTHM. He was a member of Board of Engineer Malaysia and IEEE. His research interests are electric power dispatch, distributed generation, renewable energy and meta-heuristic optimization techniques.

Mohammad Yusri Hassan is a Professor and Director of Centre of Electrical Energy Systems (CEES) in the School of Electrical Engineering, Faculty of Engineering at Universiti Teknologi Malaysia (UTM). He obtained his B.Eng. in Electrical and Electronic Engineering from University of Strathclyde, United Kingdom in 1988, M.Eng in Electrical Power Engineering from UTM in 1994 and PhD in Power System Economics from University of Strathclyde, United Kingdom in 2004. His research interests are power system economics, deregulated electricity market, transmission pricing, energy efficiency and renewable energy.

N. H. Radzi received her B.Eng. and M.Eng in Electrical Engineering (Power) from Universiti Teknologi Malaysia (UTM) in 2005 and 2009 respectively, and Ph.D from The University of Queensland, Brisbane, Australia in 2012. Currently, she is a senior lecturer in the Faculty of Electrical & Electronic Engineering at Universiti Tun Hussein Onn Malaysia (UTHM). Her research interests include transmission pricing, power system economics, energy management and renewable energy.