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Fuzzy logic controller for energy savings in a smart LED lighting system considering lighting comfort and daylight

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ABSTRACT

In commercial buildings, lighting constitutes a large proportion of energy consumption. Saving lighting energy in commercial buildings has aroused great interest among researchers. Achieving energy savings and satisfying lighting comfort are the two primary objectives in designing a lighting system. In this paper, a fuzzy logic controller was designed that considered daylight, movement information and lighting comfort. The DALI protocol was used to communicate the controller with LED luminaires. The simulation results demonstrate that lighting system without control can provide sufficient illumination. The lighting system provides wider controllability to make lighting environment operating at the most energy-saving state. The experimental results show that by using the designed controller, significant lighting energy can be saved. The office where the smart LED lighting system is installed can regulate lighting output automatically based on users' movements and allow users to choose their own lighting preferences.

1. Introduction

Commercial buildings consume more than 30% of the total primary energy [1,2]. Electric lighting is estimated to account for 20–40% of the total electricity consumed in buildings [3,4]. Appropriate control strategies for lighting systems can achieve significant energy savings. Achieving energy savings and satisfying user lighting comfort are two major considerations for designing lighting systems [5–8]. Daylight is a lighting source that most closely matches the human visual response. The use of daylight can reduce lighting power consumption, increase users' lighting comfort and improve work productivity when it is used sufficiently and reasonably [9,10].

The rapid advancement in semiconductors has brought a new generation of light sources in form of LEDs [11]. LED luminaires have been widely used in commercial lighting systems because of their long lifetime, strong cost-competitiveness, high energy efficiency and greater design flexibility [12–14]. As the accurate and flexible control of LED luminaires, centralized dispatching and decentralized control to lighting loads become feasible [15]. A LED lighting system is incorporated more smart features and has a great potential for energy savings [16–18]. Reference [19] mainly described the technical conundrum in designing a smart lighting system, and various control methods have been summarized. It has become more feasible for LED lighting systems to participate in the operation and control of a weakly regulated power system [12]. Furthermore, LED lighting loads can serve as load reserves on load scheduling.

In this study, a smart LED lighting system was installed in a test office. The installed lighting system could achieve energy savings and satisfy users' lighting comfort by considering daylight contribution and the movements of users. It consisted of a DALI control module, multiple luminaires, distributed light and motion sensing modules and a micro-controller unit [20]. The light sensors could measure the total illumination levels arising from daylight and artificial lighting independently, whereas the motion sensors could monitor whether there was a user or not [21,22]. Intelligent devices with communication can provide an opportunity to control every LED luminaire [23].

Various studies about daylight contributions and smart lighting control systems have been performed [24]. In [2,25], researchers used a simple analysis method to evaluate the potential energy savings associated with electrical lighting when it is combined with daylight use. In [26,27], lighting power density requirements were proposed to estimate energy consumption. However, the movements of the user in the office were not considered in these studies. Motion sensors were installed to monitor users' locations for offering a comfortable illumination level in occupied regions [13]. In [28,29], a utility function was proposed to demonstrate user lighting preferences, which is based on Gaussian function. In this study,

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the design focused on meeting user lighting preferences and saving lighting energy. More energy can be saved considering the daylight contributions and the real-time states in the office. A localized illumination rending strategy was presented that considered the user-occupied lighting comfort levels in [20], and two methods of lighting control were proposed to achieve energy savings and users' lighting comfort. This work would be more substantial if detailed experimental results were presented. In [30], a feed-forward neural network model was proposed to describe the relationship between the dimming levels of LED luminaires and the illumination level on a table without using simulation software. The actuation command to the luminaires was generated by a feedforward neural network control strategy. In [23], based on user preferences, a smart personal sensor network control in an LED lighting system was proposed. The system achieved significant energy savings. A fuzzy logic control system was established to control artificial lighting output by considering daylight contributions in [31]. The designed controller maintained the illumination level at a constant comfortable illumination level whereas the lighting comfort requirements had a wide range of specifications, according to users' lighting preferences. In [32], an intelligent algorithm RBFNN (radial bias function neural network) was proposed to obtain the illumination contribution from LED luminaires at any position inside the office. In order to acquire the optimal dimming levels of luminaires and design the target illumination levels, a PSO algorithm was used. Because LEDs are DC loads in nature, an LED smart lighting system played a critical role in the power management of buildings. Reference [34] provided a smart socket application for future smart buildings.

In this paper, the objective function was to minimize a weighted sum of lighting energy consumption in an office under the condition of lighting comfort. The relationship between the table illumination level and the LED luminaires was obtained by multiple measurements without daylight contributions. Light sensors and motion sensors were installed on tables to measure illumination and movement information. Based on the measured data, a fuzzy logic controller was designed to produce the required lighting output considering the lighting comfort requirements and user lighting preferences. A proportional-integral (PI) closed-loop control system was used to ensure that the actual output was in the range of the error requirement. The digital addressable lighting interface (DALI) protocol was utilized to establish a digital communication link between the controller and the LED luminaires.

The remainder of this paper is organized as follows. Section 2 describes the structure of a smart LED lighting system. In Section 3, the mathematical formulation of the LED lighting system is presented. Section 4 introduces the fuzzy logic controller considering daylight and lighting comfort. The simulation results and experiment verification are presented in Section 5 and Section 6, respectively. A final conclusions and an outlook for further work are given in Section 7.

2. Structure of a smart LED lighting system

The components of a smart LED lighting system are shown in Fig. 1. It consists of three parts: a measurement module, an information processing and decision-making module and an LED lighting system.

2.1. Measurement module

According to the design requirements, a smart lighting system requires monitoring of the real-time states in an office, including movement information and the illumination on the tables.

Light sensors were used to measure the worktable illumination from the daylight contributions and artificial lighting. Motion sensors were used to monitor whether the users are at the tables or not. Each light sensor generates a voltage signal that is related to the illumination level, and the installed motion sensor generates a low voltage level signal. The signals were sent to the controller once every second. When the motion sensors detected that all of the users have left the office, the lighting system was turned off after a delay.

The measured information was transferred to a data acquisition and processing module, which is an important element for decision-making strategies.

2.2. Information processing and decision-making

This section is the core of the design of a smart lighting system. It includes two main units: the information processing unit and the decision-making unit. Considering daylight performance and the movements of users in the office, the decision-making unit must process the information and provide dimming commands to the LED drivers to regulate the artificial lighting output. The main objective is to achieve energy savings under lighting comfort requirements. However, it is difficult to precisely define lighting comfort. A fuzzy logic controller was designed take these considerations into account. The output of the designed controller is a group of artificial lighting illumination requirements. With a PI closed-loop control system, the actual output of LED luminaires

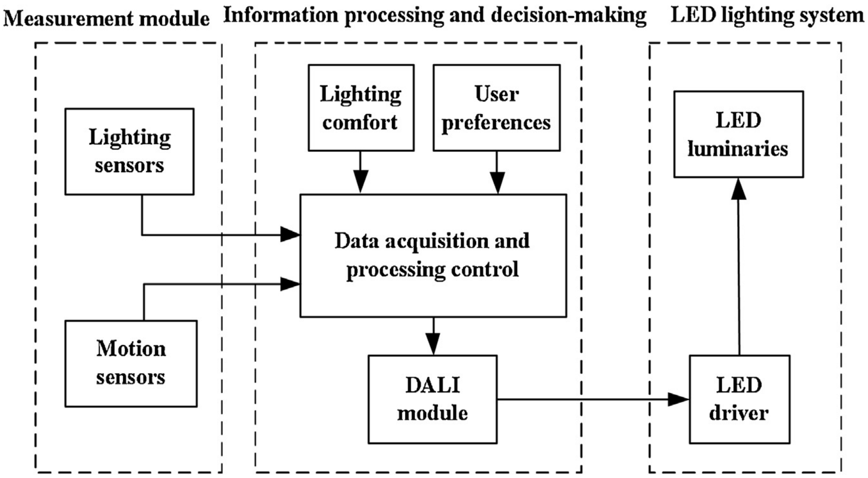

Fig. 1. Block diagram of a smart LED lighting system.

could follow the designed lighting output. Using this control strategy, the illumination level on the table can maintain at a constant level.

2.3. LED lighting system

The LED lighting system consists of the DALI control module and multiple LED luminaires. Each LED luminaire was equipped with a DALI constant-current driver, which can receive instruction signals to regulate the lighting output.

The DALI protocol was chosen to provide a digital communication link to the designed controller and luminaires. The DALI protocol is an intelligent control standard which is specially designed for a lighting system. The DALI control module was provided for addressable control of distributed DALI-equipped LED luminaires. The DALI control module has many advantages, e.g. distinguished functionality, high flexibility and low installation cost. The protocol has feasible integration and aggregation. Moreover, it is feasible to realize centralized control of multiple LED luminaires.

A dimmable constant-current drive circuit that has many advantages compared to a constant-voltage drive circuit was chosen. An advantage of this circuit is that the consumption of LEDs decreases while the temperature is increasing. In Fig. 2, the current through the luminary remains constant, but the voltage of the luminaire is reduced as the junction temperature increases. Thus, the power consumption of the LED luminaire is decreased. Another advantage is that all LED luminaires in a constant-current drive circuit system have high brightness uniformity.

3. Problem formulation

3.1. Objective functions

The objective functions of a smart LED lighting system are comprised of two important requirements: minimizing the total lighting consumption and satisfying users' lighting comfort.

3.1.1. Lighting energy consumption

Reducing the lighting energy consumption has great potential in energy saving applications. The objective is to minimize the total lighting energy consumption, which can be expressed as follows:

$$min\ f_1 = \sum_{i=1}^{m} d_i \times p \times t_w. \tag{1}$$

where f_1 is the total lighting energy consumption, d_i is the duty cycle of a group of LED luminaires, p represents the power consumption of a group LED luminaires and t_w is the total office hours of the LED luminaires.

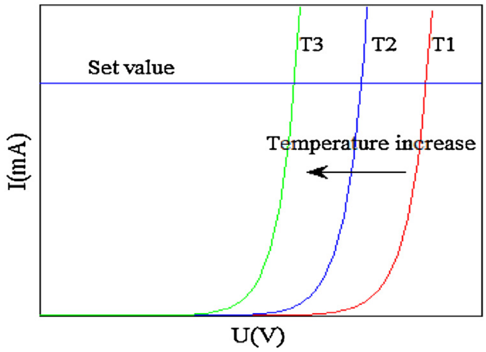

Fig. 2. Volt-ampere characteristics curve of LED luminaires.

3.1.2. Lighting comfort requirements

Lighting comfort is a vital component to improve indoor environmental quality, which should not be compromised by energy saving measures. The objective function is to maximize the users' total lighting comfort levels:

$$max\ f_2 = \sum_{i=1}^{n} c_i. \tag{2}$$

where c_i is the lighting comfort level, which is based on a Gaussian function.

3.2. Constraints

3.2.1. Control constraint

LED luminaires can dim at a duty cycle within the range of 100%–0%, which can be expressed as follows:

$$0 \le d_i \le 1, i = 1, \cdots, m.$$

The daylight source is uncontrollable but can be measured. Daylight is an important element in creating a pleasant lighting environment. Suppose the daylight contributions cannot provide sufficient illumination levels on tables and is lower than the comfortable illumination level.

$$0 \le N_i \le E_{ch}, i = 1, \cdots, m. \tag{4}$$

where N_i represents the daylight contributions on table m. E_{ch} is the upper limit illumination level considering lighting comfort.

Considering an office has n LED luminaires and m worktables. The illumination level on the worktables can be represented as a linear function:

$$E = A \times d + N. \tag{5}$$

where

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{bmatrix}, \tag{6}$$

$$E = [E_1, E_2, \cdots, E_m]^T, \tag{7}$$

$$N = [N_1, N_2, \cdots, N_m]^T, \tag{8}$$

$$d = [d_1, d_2, \cdots, d_n]^T. \tag{9}$$

E_m is the total illumination level on table m, a_{mn} represents the illumination contribution on table m from luminaire n, $\boldsymbol{d}_n$ is the duty cycle of luminaire n generated by the designed controller and N_m represents the daylight contributions on table m, A is the illumination transfer matrix describing the effect of the luminaires at worktables.

3.2.2. Lighting comfort constraint considered user lighting preferences

Based on different users' lighting preferences, utility functions were used to evaluate the lighting comfort of the users. In fact, lighting comfort is to a degree in conflict with energy savings. Color temperature also plays an important role in determining lighting comfort. The relationship between the comfortable illumination range and color temperature is shown in Fig. 3. The higher the color temperature, the wider the comfort illumination levels range.

Typically, users in offices prefer environmental conditions that are more productive than conditions in which they feel uncomfortable. Utility functions are used to determine the lighting comfort of

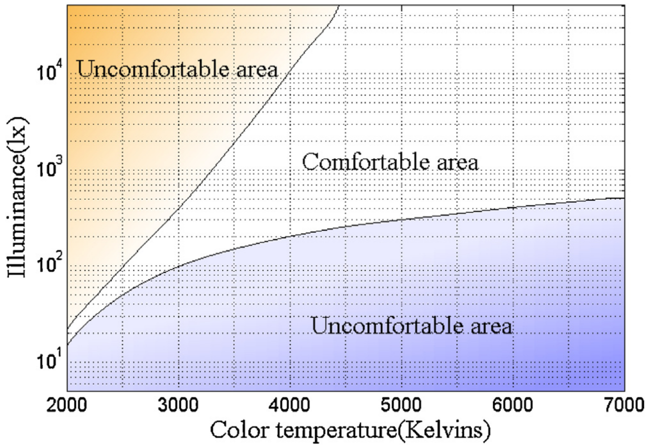

Fig. 3. Comfort level of the Kruithof curve.

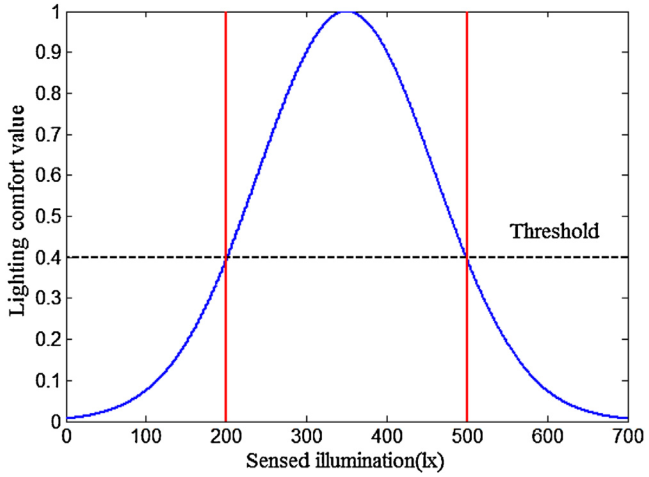

Fig. 4. Requirements of user lighting comfort level.

users. The utility function is different for each user. A utility function value corresponds to a higher comfortable illumination level [27]. In this paper, the lighting comfort level was given by a Gaussian function with the parameters μ, σ and t. The function is shown in Eq. (10):

$$f(x) = \left\{ \begin{array}{l} exp(\dfrac{-(x\text{-}\mu)^2}{2(\sigma)^2}), ifx \in \left[\mu - \sigma\sqrt{-2\ln(t)}, \mu + \sigma\sqrt{-2\ln(t)}\right] \\ 0, otherwise \end{array} \right\} . \quad (10)$$

The parameters of the function are set with $\mu = 120$, $\sigma = 350$ and $t = 0.4$. The utility function is shown in Fig. 4, 350 lx is regarded as the most comfortable illumination level for users.

Thus, the lighting comfort constraints in this paper can be expressed as follows:

$$\left\{ \begin{array}{l} E_{cl} \le E_m \le E_{ch}, i = 1, \cdots, m \\ t \le c_i \le 1, i = 1, \cdots, n \end{array} \right. . \quad (11)$$

where E_{cl} is the lower limit of illumination level that considers lighting comfort, E_{ch} is the upper limit of illumination level that considering lighting comfort, E_m is the total illumination level on table m, t is the threshold level on lighting comfort and c_i is the lighting comfort threshold level of one user.

3.3. Model solution

In this paper, the objective functions are to minimize energy consumption and to maximize the users' lighting comfort requirements. Considering the requirements of the lighting preferences of users and the daylight contributions, the objective functions were expressed as follows:

$$\{ \begin{array}{l} \min f_1 = \sum_{i=1}^{m} d_i \times p \times t_w \\ \max f_2 = \sum_{i=1}^{n} c_i \end{array} , \quad (12)$$

In this paper, the main objective method was adopted to transform the multi-objective optimization functions into single-objective functions [33]. The main objective was to minimize energy consumption. Lighting comfort levels can be regarded as a constraint. Thus, the single-objective function can be written as follows:

$$\left\{ \begin{array}{l} \min\ f_1 = \sum_{i=1}^{m} d_i \times p \times t_w \\ E_{cl} \le E_i \le E_{ch} \end{array} \right. , \quad (13)$$

4. Designed fuzzy logic controller

Fuzzy logic controllers have been introduced in the design of indoor lighting control systems [35,36]. These controllers have the advantage of being robust and relatively simple to design because they do not require knowledge of the exact models.

Lighting comfort is a subjective evaluation of users' satisfaction of the indoor environmental quality, which is difficult to rank precisely with exact boundaries. Fuzzy mathematics is an appropriate tool for the assessment of lighting comfort. A comprehensive fuzzy algorithm involving the daylight contributions and artificial lighting was proposed to evaluate users' lighting comfort.

4.1. Fuzzification

The proposed fuzzy logic system in this paper consists of two input variables and one output variable. The various inputs and outputs were divided into five fuzzy subsets.

Let a = {very dark (VD), dark (D), medium (M), light (L), very light (VL)} denote the domain of daylight illumination ranks. Each rank is depicted by a membership function, as shown in Fig. 5. Triangular and trapezoid functions were used.

Let b = {very low (VL), low (L), medium (M), high (H), very high (VH)} denote the domain of artificial lighting ranks. Each rank is depicted by a membership function of trapezoid and triangular form, as shown in Fig. 6.

Let c = {very uncomfortable low (VUL), uncomfortable low (UL), comfortable (C), uncomfortable high (UH), very uncomfortable high (VUH)} denote the domain of comfort illumination ranks. Each rank is depicted by its own membership functions of triangular or trapezoid forms, as shown in Fig. 7.

4.2. Inference method

In this paper, the algorithm requires 25 fuzzy control rules, which are based on a sensitivity analysis. The daylight output has a higher weight factor for lighting comfort than artificial lighting. To operate the fuzzy combination, Mamdani's method with Max-Min was used. A fuzzy system is a set of if-then rules that maps inputs to output [35]. Table 1 showed the rules for the designed fuzzy logic

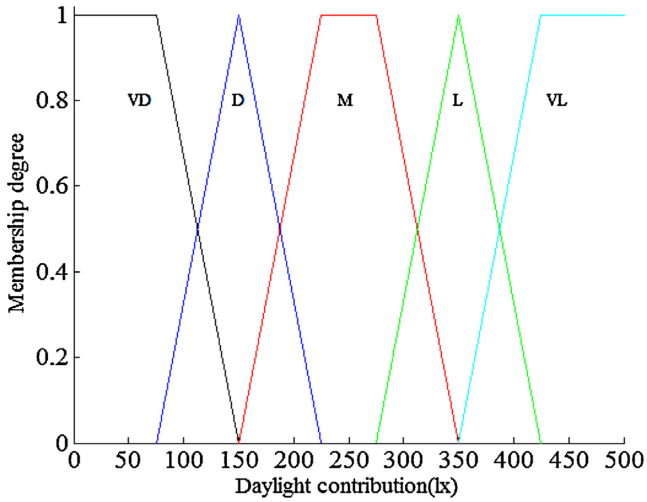

Fig. 5. Daylight contribution membership functions.

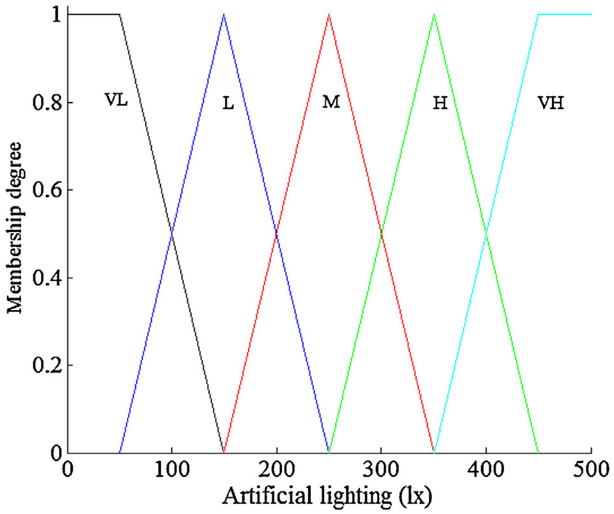

Fig. 6. Artificial lighting membership functions.

Table 1
Inference rules of designed fuzzy logic controller.

Artificial lighting	Daylight contribution				
	VD	D	M	L	VL
VL	VUL	VUL	UL	C	C
L	UL	UL	C	C	UH
M	C	UL	C	UH	VUH
H	C	C	UH	VUH	VUH
VH	UH	UH	UH	VUH	VUH

controller. A 3-D visualization of the inference rules was shown in Fig. 8.

4.3. Defuzzyfication

The last stage of the designed fuzzy logic controller is the defuzzification. The center of the area algorithm was used to convert the fuzzy subset duty cycle changes to real numbers, which was considered a logical and rigorous method [36,37]. The control system of rules was formally given by the following equation:

$$CI = \frac{\sum_{i=1}^{n} \mu(CI_i)CI_i}{\sum_{i=1}^{n} \mu(CI_i)}. \tag{14}$$

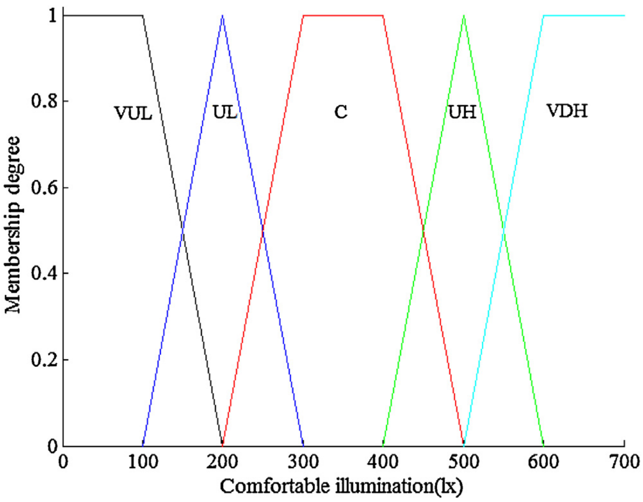

Fig. 7. Comfortable illumination membership functions.

where $\mu\ (CI_i)$ is the activation degree on rule i. CI_i is the center of the Max-Min composition at the output membership functions. CI is the comfortable illumination level.

4.4. Fuzzy logic control strategy

The block diagram of proposed control strategy considering lighting comfort was shown in Fig. 9. Based on the illumination level measured by the light sensors, the output of the designed fuzzy logic controller was the comfortable illumination level. According to lighting preferences and motion signals, a decision-making algorithm was discussed. The required artificial output was given by using the proposed algorithm.

A PI closed-loop control system was utilized to allow the actual lighting output to follow the required lighting output. The principle of the closed-loop control system can be written as follows:

$$d_i = K_P e_n + \frac{K_I}{J}\sum_{j=0}^{J-1} e_{n-j}. \tag{15}$$

where K_P and K_I are the coefficients of the P and I control branches, which are used to weight the error and an accumulation of past error, respectively. e_n is the artificial lighting output error, d_i is the control signals of the LED luminaires.

5. Simulation results

5.1. Office configuration

An office at Shandong University in China that faces north was selected for this study. The office lacated on the third floor, with dimensions of 12.6 m × 6.6 m × 2.75 m. There are 9 sets of LED luminaires with 2 × 18 W in the office. A simulation model created by DIAlux was shown in Fig. 10. The detailed parameters of the LED luminaires were shown in Table 2.

The detailed office parameters are shown in Table 2.

5.2. Isolines simulation results

According to the office parameters presented in Table 2, Fig. 11 shows the isolines illumination results with full brightness in the office. The daylight contributions were not considered in this simulation. As shown in Fig. 11, the highest illumination exists in the center of the office, the table illumination is higher than the comfortable illumination and some unoccupied areas have higher

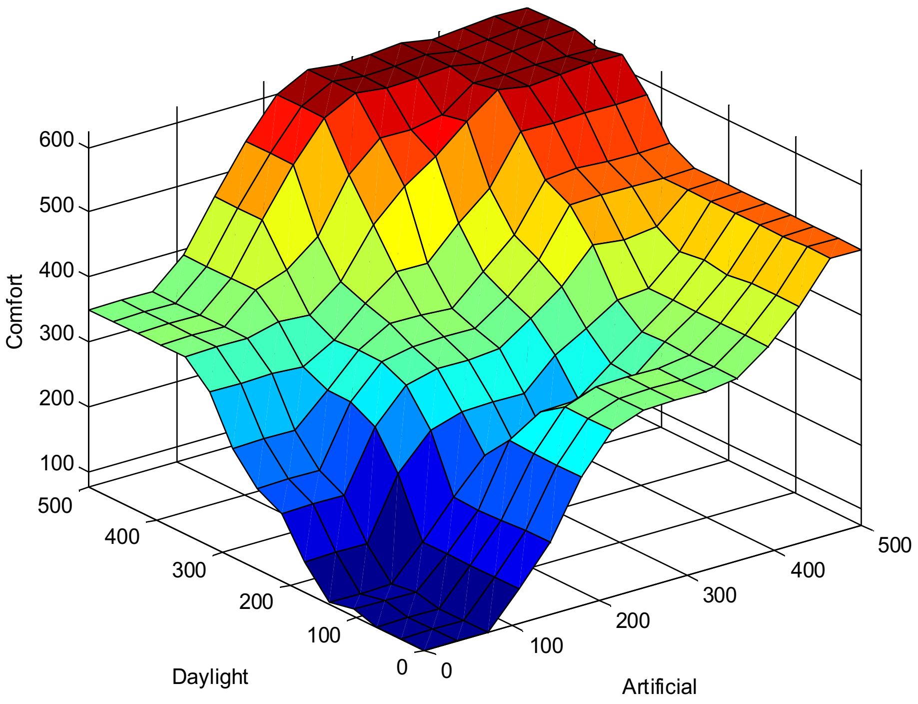

Fig. 8. 3-D visualization of the inference rules.

Table 2
Parameter values in simulation model.

Parameters	Value
Worktable height	0.75 m
LED power consumption	18 × 18 W
Utilization factor	0.85
Light loss factor	0.8
Floor reflection coefficient	0.3
Ceiling reflection coefficient	0.5
Wall reflection coefficient	0.7
Furniture reflection coefficient	0.4

Table 3
Lighting power consumption under different scenarios.

Illumination (lx)	Power consumption (W)	Power savings (W)	Savings percentage
350	287.64	36.36	11.22%
350 (absence)	270.36	53.64	16.56%
300	224.64	99.36	30.67%
200	140.76	183.24	56.56%

illumination levels. In other words, the lighting system is operating in a non-optimal state, which indicates a great potential for energy savings by the use of appropriate lighting control strategies.

According to the Kruithof curve presented in this paper, in a lighting system with a color temperature of 4000 K, the maximum energy savings can be saved at a lower limit illumination within the comfort constraint. Based on the proposed utility function, the most satisfying lighting comfort level was 350 lx. The isoline simulation results were shown in Fig. 12a, where each table illumination level was set to 350 lx. In Fig. 12b, the illumination level on the tables was regarded 300 lx based on various users' lighting preferences

Table 3 shows the lighting power consumption in different scenarios with the proposed control strategy. The lighting power consumption without control is 324 W. In the scenario with the most comfortable lighting performance, the lighting power consumption is 287.64 W, i.e., approximately 11.22% of the energy can be saved, and an additional 5.34% energy savings can be achieved by considering user movement information. In consideration of users' lighting preferences, 30.67% energy savings can be achieved. Under the lowest illumination at the lower limit level, the LED lighting system consumes 56.56% less energy than LED luminaires with full brightness.

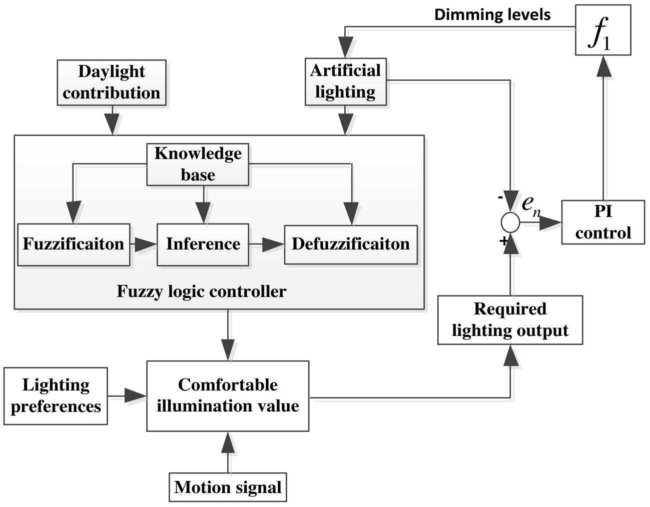

Fig. 9. Block diagram of the fuzzy logic controller.

6. Experimental verification

6.1. Implementation test-bed

An office with an area of 83 m^2 at Shandong University in China was selected. The deployment of a smart LED lighting system was depicted in Fig. 13. DALI dimmable constant-current drivers were used to output DC power to each of the LED luminaires, which have a high power factor. The drivers can receive DALI dimming instruction signals to control the LED luminaires. A platform of light sensors and motion sensors was employed in this research. The platform was based on an ultra-low-power STM32103ZET6 micro-

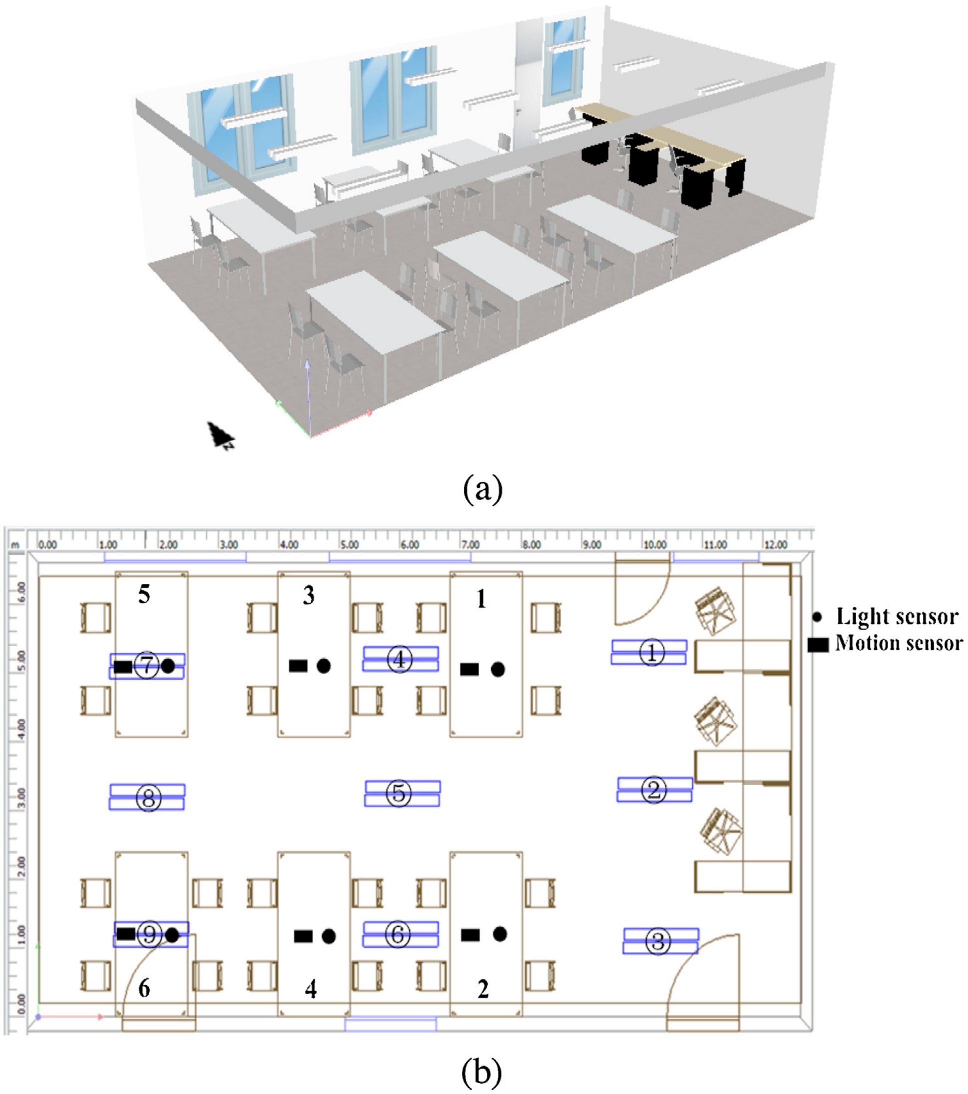

Fig. 10. Layout of the two types of LED luminaires in the test office.

controller. Based on the data received from the RS485 bus, the required artificial lighting output was produced via the designed fuzzy logic controller. By using Ethernet RJ45, the DALI control module was connected with a PC. Users could select their own lighting preferences via the touch panel.

6.2. Experiment results

To measure daylight contribution on the tables, LED luminaires were turned off completely. Throughout the working day, daylight illumination on tables was measured at each hour during office time on October 8, 2015. The measured data were shown in Table 4. During each hour, the daylight contributions changed linearly.

Considering the daylight contributions on the tables, by using the designed controller and proposed control strategy, the illumination levels on the tables were shown in Fig. 14. For example, considering the daylight contribution on table no. 3 at 10:00 a.m. to evaluate the performance of the designed PI closed-loop controller which was used to track the actual illumination level compared to the desirable illumination level. At steady-state conditions, the maximum percentage error between the measured illumination level and the reference level is 2.64%. The percentage error comes from the following factors: the sensors, the location of installed sensors and the movement of users.

Table 4
Daylight illumination levels on the tables.

Time	Table No.					
	1	2	3	4	5	6
8:00	52	24	93	28	140	23
9:00	72	32	111	36	160	28
10:00	76	35	115	40	167	30
11:00	80	40	126	45	176	32
12:00	86	42	130	52	190	42
13:00	88	50	132	60	230	52
14:00	96	50	140	70	240	56
15:00	75	40	125	58	215	42
16:00	60	34	112	46	182	32
17:00	45	30	102	32	150	26

In Scenario 1, the table illumination level was measured with all of the luminaires operating at full brightness without control. The illumination value considering daylight contribution was higher than the most comfortable level. In Scenario 2, the table illumination value was maintained at the most comfortable level. When the motion sensor detected that a user leaves the work area, the illumination level is decreased until the user returns to the work area. In Scenarios 3 and 4, users choose their own lighting preferences according to different working requirements, and the conditions in

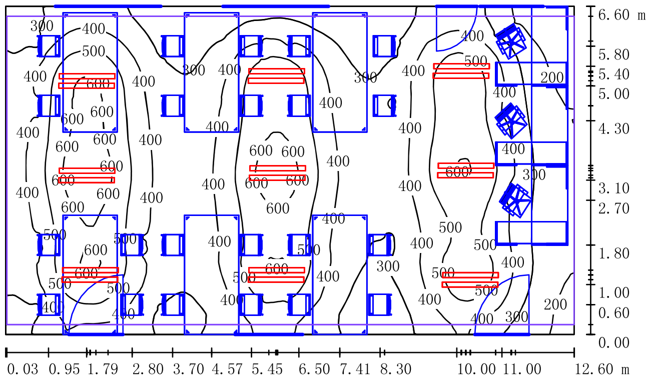

Fig. 11. Isolines simulation results of LED luminaires.

which users leave the work area and return to the work area were considered. In Scenario 5, based on the proposed lighting comfort requirements, the table illumination level was kept at the lower limit of the illumination level.

Suppose that the daylight contributions on the table changes linearly during each hour, as shown in Fig. 15.

The blue curve represents the lighting power consumption without control. The green curve is the lighting power consumption with all of the tables maintaining the most comfortable illumination level. The saving potential is equal to 34.26% of lighting power consumption without control in a day. An additional 10% energy savings can be achieved when movement is considered. The lighting power consumption with various user lighting preferences was shown as the purple curve. Nearly 57.06% of lighting energy can be saved when the preference illumination level is 300 lx. A significant amount of energy can be saved if the illumination is maintained at the lower limit illumination. At that limit, the average table illumination level was 200 lx, and the power demand will decrease significantly within a short time range in a large number of offices. LED lighting loads have great potential as frequency controlled reserve.

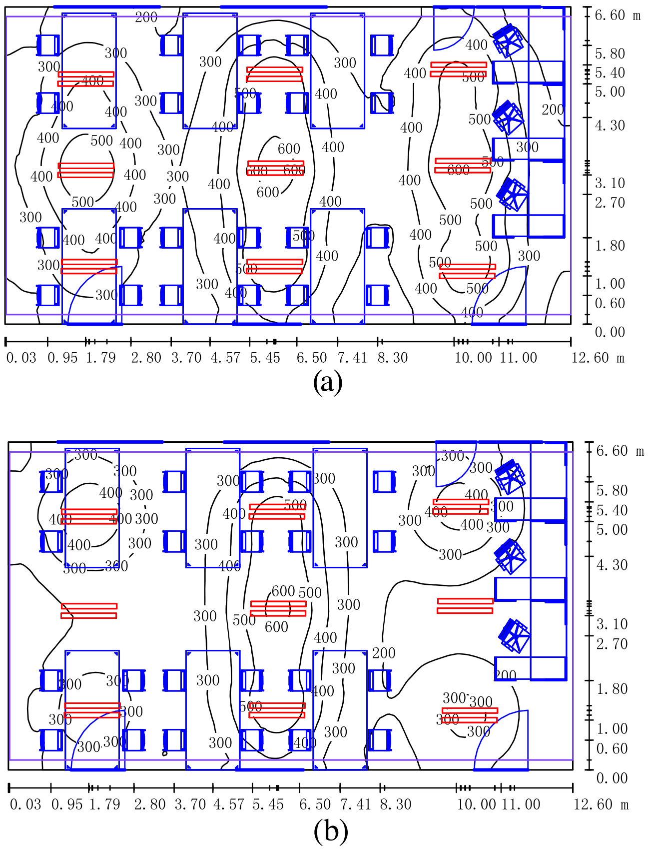

Fig. 12. Isolines simulation results: (a) at the most comfortable illumination and (b) illumination based on users' lighting preferences.

7. Conclusions and future study

In this paper, a smart LED lighting system was installed in a test office (at Shandong University in China). The relationship between

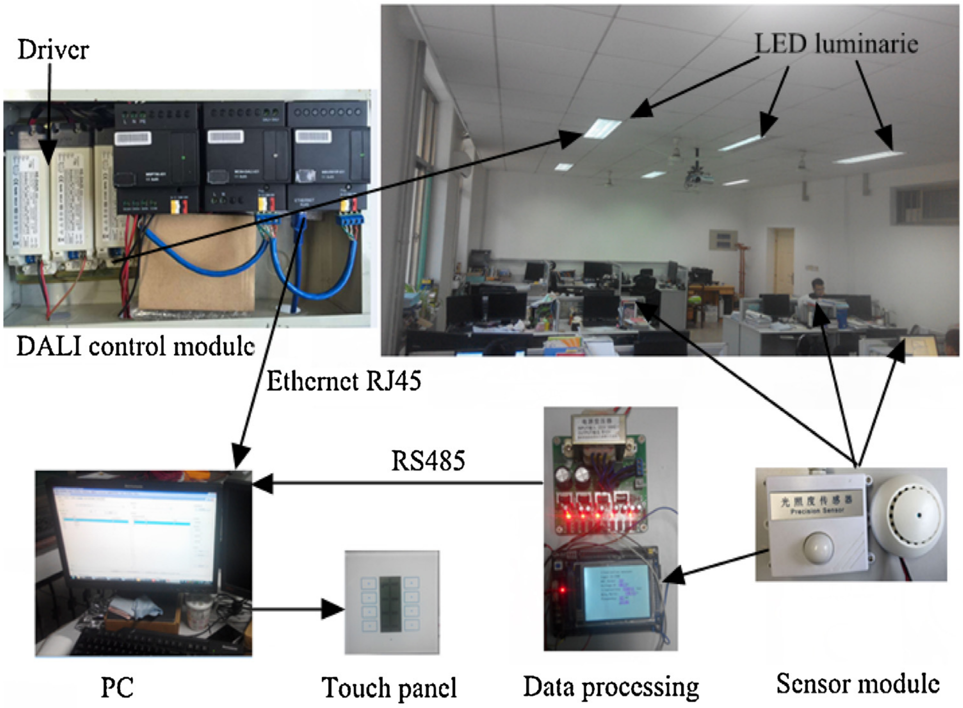

Fig. 13. Deployment of a smart LED lighting system.

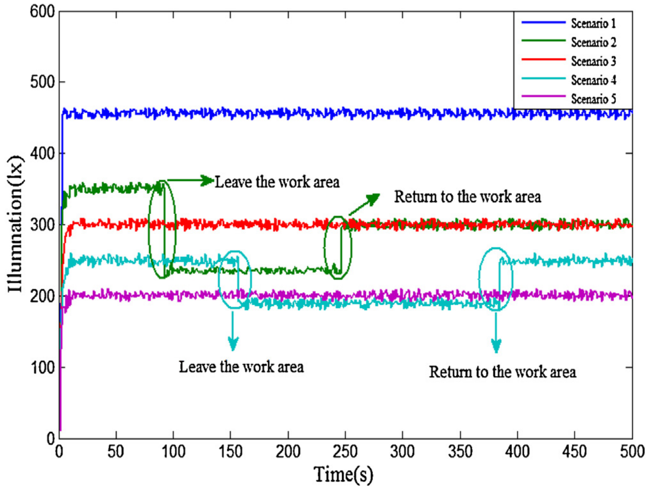

Fig. 14. Actual measurement of illumination level on Table 3.

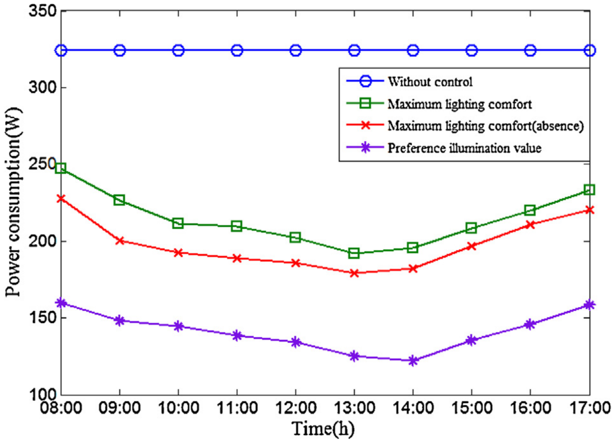

Fig. 15. Lighting power consumptions during office hours.

the table illumination and the lighting output was obtained by using multiple measured data. Saving lighting energy and satisfying user lighting comfort are the two primary considerations in designing a lighting system. A fuzzy logic controller was designed in which the daylight contribution and user lighting comfort were considered. After the lighting system was installed, the users in the test office could choose their own comfortable illumination levels. The experimental data were collected on October 8, 2015. According to the experimental data, the illumination levels on the tables remained unchanged, despite the constantly changing amount of daylight. Based on various lighting preferences, significant energy can be saved.

Because of the flexible control and high integration levels of LED lighting systems with advanced protocol, decentralized control for LED lighting systems has become possible. Non-critical loads, such as the HVAC loads and the LED lighting loads, could participate in power system operation and scheduling on a weakly regulated microgrid or with a high penetration of renewable generations into conventional power system. Future work in this study is aimed at lighting loads as frequency controlled reserve to abnormal frequency events in power systems.

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