Distributed Control of Illuminance and Color Temperature in Intelligent Lighting System

[1]Chitose Tomishima, [2]Mitsunori Miki, [1]Maiko Ashibe, [3]Tomoyuki Hiroyasu, and [2]Masato Yoshimi

[1]Graduate School of Engineering, Doshisha University.
[2]Depertment of Science and Engineering, Doshisha University.
[3]Department of Life and Medical Sciences, Doshisha University.
1-3 Tatara Miyakodani, Kyotanabe, Kyoto 610-0321, Japan
{ctomishima@mikilab,mmiki@mail}.doshisha.ac.jp,asshi219@gmail.com,{tomo@is,myoshimi@mikilab}.doshisha.ac.jp

Abstract. This reserch proposes a method to provide an appropriate illuminance and color temperature in an office lighting environment for individual workers. For the control algorithm, based on the optimization method called Simulated Annealing (SA), a method including a neighborhood design mechanism for the design variables instead of a temperature parameter was used. In addition, for changes in the luminous intensity of high color temperature light and low color temperature light, five neighborhoods were adaptively used. Through the experiment using the daylight color fluorescent lamps and warm white color fluorescent lamps, the illuminance and color temperature converged into the target values.

Key words: intelligent lighting system, autonomous distributed control, energy saving, Illuminance, Color Temperature

1 Introduction

Recently, the enhancement of the intellectual productivity, creativity and comfort of office workers are being focused on. A great deal of research into the effects of office environments on intellectual productivity has already been conducted. This research has reported that intellectual productivity is enhanced by improving the office environment [1]. Research focusing on lighting environments in offices has reported that changes in illuminance and color temperature corresponding to biological rhythm enhance intellectual productivity [1]. There is also research reporting that individual workers need different illuminance depending on job description [2]. With this background, the authors researched an intelligent lighting system that provides different levels of illuminance for individual office workers [3]. The intelligent lighting system is a distributed autonomous lighting system that provides an appropriate illuminance to an appropriate location. Such intelligent lighting system have already been tested in actual offices and their high performance and practical utility have been verified.

The intelligent lighting system focuses on illuminance that is an element of the light environment. Illuminance is the brightness of any given place. Color temperature is also important for lighting environments, however. This research focuses on illuminance and color temperature and proposes the individually distributed control of illuminance and color temperature. By providing different levels of illuminance and color temperature to office workers, a light environment that depends on individual conditions can be realized. Through this, it is expected that intellectual productivity, creativity and comfort will be further enhanced. Color temperature will be explained in detail in the following section.

2 Color Temperature

Color temperature is an index that shows the color of light. If a black body is heated, light is eradiated. The temperature of the black body is the color temperature of the light. K (Kelvin) is used for the unit. Lower color temperatures give off a reddish color, while higher color temperatures give off a bluish color. Fluorescent lamps are classified into " daylight color (about 5000 to 6500 K) ", " cool white color (about 4100 to 4500 K) ", " warm white color (about 2700 to 3500 K) " from several reteratures[4–7]. In Japan, the fluorescent lamps with color temperatures of 5000 K are used in common offices.

Various research efforts on the effects of color temperature on humans have been conducted. Research about the effects of color temperature on arousal has reported that light sources with higher color temperatures increase arousal more than lower color temperatures [8]. In addition, higher color temperatures accelerate the excitement of the autonomic nervous system more than lower color temperatures [9]. Research has been conducted on color temperatures appropriate for human behavior, reporting that it is important to provide color temperatures appropriate for living conditions (the design of the lighting environment) [1]. The effects of higher color temperatures on humans have also been researched. Philips conducted an experiment using lights with color temperatures of 17000 K (Acti-Viva fluorescent lamps) at factories and offices. This research showed high color temperature light enhanced work efficiency (e.g., memory was increased, concentration was enhanced and discretion was improved) [10]. Kruithof reported that a lower illuminance was comfortable in lower color temperatures, while a higher illuminance was comfortable in higher color temperatures [11].

As indicated above, it is believed that individual office workers require different levels of illuminance and color temperature depending on the content of their work, conditions and moods. This research proposes an intelligent lighting system that allows for individually distributed control of illuminance and color temperature in an office.

3 Proposed Intelligent lighting system

3.1 Outline of the previous system and new system

In the intelligent lighting system, multiple luminaires are connected to the network. Each luminaire satisfies illuminance requested by a user using a built-in microprocessor and a distributed autonomous system or algorithm [3]. The appropriate illuminance is provided to the appropriate location simply by the user setting the target illuminance on the illuminance sensor, without using the position information from the lights and sensors. In addition, the power usage is reduced.

In conventional intelligent lighting system, illuminance is controlled by a distributed control method. This research focuses on illuminance and color temperature and proposes a distributed control of illuminance and color temperature. In this study, as shown in Fig. 1, a chroma sensor and two lights with different color temperatures, i.e., a higher color temperature light and a lower color temperature light, provide individually distributed control illuminance and color temperature. Different levels of illuminance and color temperature are provided in different places by individually distributed control of these lights.

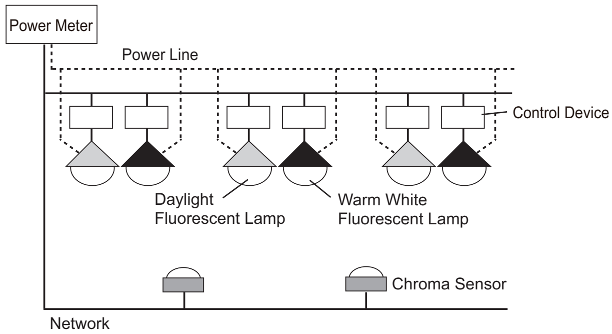


Fig. 1. Configuration of the intelligent lighting system

3.2 Control algorithm

In the proposed system, lights containing controllers adjust luminous intensity autonomously through a distributed autonomous control algorithm. Luminous intensity is the brightness of a light source. This algorithm is the Adaptive Neighborhood Algorithm using Correlation Coefficient (ANA/CC) [3] containing a neighborhood design mechanism variable instead of a temperature parameter based on Simulated Annealing (SA).

The purpose of this system is to minimize power usage while satisfying the target illuminance and target color temperature set in each sensor. The question to satisfy the purpose of this system is understood as an optimization problem. The purpose of this system is formulated to meet the objective function. The objective function value is maintained by each light independently. Each light minimizes its objective function to optimize the entire system. Equation 1 shows the objective function.

$$f = P + w_1 \sum_{j=1}^{n} L_j + w_2 \sum_{j=1}^{n} T_j \tag{1}$$

$$P = \sum_{i=1}^{m} Cd_i$$

$$L_j = \begin{cases} R_j(Lc_j - Lt_j)^2, & 50 < (Lc_j - Lt_j) \\ 0, & -50 \leq (Lc_j - Lt_j) \leq 50 \\ R_j(Lc_j - Lt_j)^2, & (Lc_j - Lt_j) < -50 \end{cases}$$

$$T_j = \begin{cases} R_j(Tc_j - Tt_j)^2, & 50 < (Tc_j - Tt_j) \\ 0, & -50 \leq (Tc_j - Tt_j) \leq 50 \\ R_j(Tc_j - Tt_j)^2, & (Tc_j - Tt_j) < -50 \end{cases}$$

$$R_j = \begin{cases} r_j, & r_j \geq Threshold \\ 0, & r_j < Threshold \end{cases}$$

$n : number\ of\ chroma\ sensors,\ m :\ number\ of\ lighting\ fixtures,\ w_1, w_2 :\ weight$

$P :\ electricity\ usage\ amount,\ Lc :\ current\ illuminance,\ Lt :\ target\ illuminance$

$Cd:$ *luminous intensity*, $Tc:$ *current color temperature*, $Tt:$ *target color temperature*
$r:$ *correlation coefficient*, $Threshold:$ *threshold value*

The objective function value is the sum of electricity, illuminance restriction and color temperature restriction. The convergence range of illuminance and color temperature is set to target value ± 50. In other cases, the objective function value is increased as a penalty. Illuminance restrictions and color temperature restrictions are obtained by multiplying the square of the difference between the target value and the current value by the correlation coefficient concerning luminous intensity variation and illuminance variation. If the correlation coefficient is less than the set threshold, it is multiplied by 0. In other words, even if the chroma sensor does not satisfy the target, when the correlation coefficient to the chroma sensor is low, no penalty is given to the objective function. As a result, we can narrow the target of optimization to chroma sensors with higher correlation or chroma sensors with a higher degree of incidence to improve the accuracy to satisfy the target illuminance, target color temperature and convergence time. In addition, illuminance restrictions and color temperature restrictions are multiplied by weight w_1 and w_2 to make it possible to determine the preference among illuminance convergence, color temperature convergence and minimization of electricity based on the value of the weight. The flow of the control algorithm is shown below:

Step1： All lights are turned on with the initial luminous intensity.
Step2： Obtain sensor information from each chroma sensor (i.e., sensor ID, current illuminance, target illuminance, current color temperature and target color temperature) and electricity usage amount from power meter. Target function value is calculated from these values.
Step3： Each light selects one neighborhood from among the neighborhood set by the correlation coefficient described later.
Step4： The next luminous intensity is randomly generated for the neighborhood determined in Step 3. Lights are turned on with the next luminous intensity.
Step5： Obtain sensor information from each chroma sensor and electricity usage amount from power meter.
Step6： Calculate the objective function value from the sensor information and electricity usage amount in the state the lights are turned on with the next luminous intensity.
Step7： Calculate the correlation coefficient from the obtained variation in the illuminance from the chroma sensors and the variation in the luminous intensity of the lights.
Step8： If the objective function value is favorable, the luminous intensity is fixed and the process returns to Step 2. If the objective function value changes for the worse, the changed luminous intensity is cancelled on the basis of the calculation and the process returns to Step 2.

By this algorithm, the degree of incidence of the lights and the chroma sensors is determined, the target illuminance and target color temperature are satisfied and the electricity usage amount is saved in a short time. The reason the process returns to Step 2 instead of Step 3 in Step 8 is to adapt to changes in the environment such as the transfer of chroma sensors and the incidence of outside light.

3.3 The correlation coefficient

It is effective to understand the positional relationship between a light and a sensor in order to satisfy the target illuminance and target color temperature and realize an electrical power saving state in a short time. It is efficient to use the correlative relationship between the variation in the luminous intensity of the lights and the variation in the illuminance from the sensors to understand the positional relationship in an autonomous manner. The chart in Fig.2(b) shows the history of the correlation coefficient in the positional relationship between the lights and sensors as shown in Fig.2(a). The correlation between the variation in the luminous intensity of the Light1 and the variation in the illuminance from the sensors becomes higher, and the correlations between the variation in the luminous intensity of the Light2 and 3 and the variation in the illuminance from the sensors becomes lower. By putting this correlation coefficient in equation 1 and using it when generating the next luminous intensity, it is possible to shorten the time to realize the optimum lighting pattern.

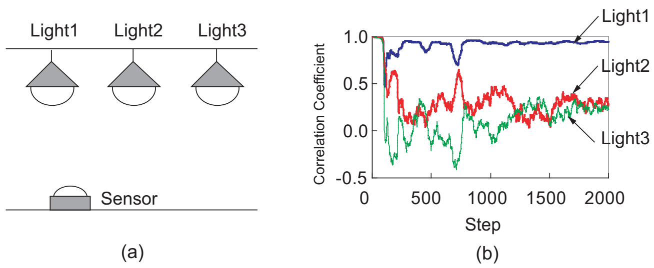


Fig. 2. Correlation coefficient between the lights and the sensors

3.4 Neighborhood design

Neighborhood is the variation range of the design variable. Neighborhood design refers to the design of the variation range in an appropriate manner. The five neighborhoods shown in Fig.3 are used to randomly increase and decrease the light of the lights. Type A is the neighborhood focusing on decreasing luminous intensity rapidly. Type E is the neighborhood that increases luminous intensity rapidly. Type C is the neighborhood that adjusts luminous intensity when illuminance and color temperature constraint conditions are satisfied. Types B and D are neighborhoods that have intermediate characteristics. The value in Fig.3 is the ratio of the total luminous intensity of the lights (100 % luminous intensity) and the best value obtained in the experiment.

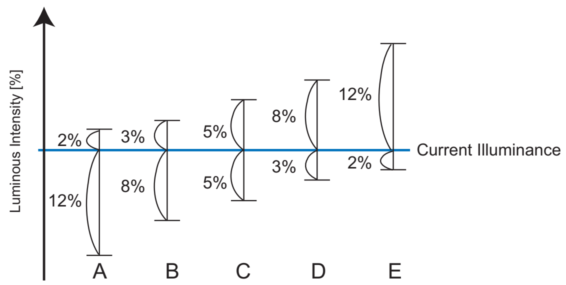
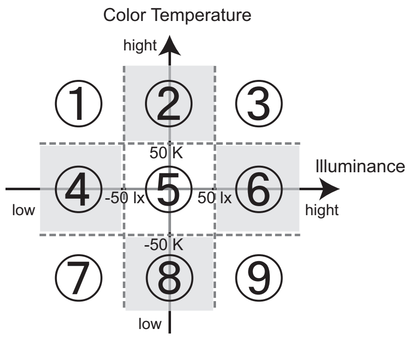


Fig. 3. Five types of the neighborhood ranges (variation range of the design variable)

Based on the illuminance information and color temperature information, the appropriate neighborhood is selected from the five neighborhoods in accordance with neighborhood design. Fig.4 shows the rules of neighborhood design used in this algorithm. The origin in Fig.4 is the target illuminance and target color temperature given to the sensor. As mentioned above, target illuminance ± 50 lx and target color temperature ± 50 K is the convergence range. An illuminance variation of ± 50 lx cannot be detected by humans [12]. In addition, there is little research about variations in color temperature that can be detected by humans. In this research, it was set to ± 50 K based on a preliminary experiment. In conventional intelligent lighting system realizing individual illuminance, the only constraint conditions are the multiple levels of illuminance. If the luminous intensity is increased, the electricity usage amount is also increased, but the restriction on the illuminance level was satisfied. When both the illuminance and color temperature are controlled closer to the target value, however, it is difficult to adjust luminous intensity. In higher color temperature lights, if the luminous intensity is increased, illuminance and color temperature also increase. Meanwhile, in lower color temperature lights, if the luminous intensity is increased, illuminance increases while color temperature decreases. Therefore, for illuminance and color temperature, there are three states, i.e., convergent to target value, lower than target value and higher than target value. As shown in Fig.4 there are nine states in total. In each region, it is possible to converge into the target illuminance and target color temperature by determining the neighborhood used by higher color temperature lights and lower temperature lights. For example, in the range of type A, the illuminance is low and the color temperature is high. At this time, illuminance is increased and color temperature is decreased by increasing the luminous intensity of the lower color temperature light. Accordingly, the neighborhood of the higher color temperature light that does not need to be changed is type C in Fig.4. The neighborhood of the lower color temperature light for which the luminous intensity should be increased is type E in Fig.4. The table in Fig.4 shows the combination of light neighborhoods in a total of nine regions.



Region	Neighborhood	
	Neutral color Fluorescent Lamp	Warm White Fluorescent Lamp
①	C	E
②	B	D
③	A	C
④	D	D
⑤	C	C
⑥	B	B
⑦	E	C
⑧	D	B
⑨	C	A

Fig. 4. Determination method of the neighborhood designs

As shown above, rapid convergence is accelerated by considering the characteristics of each light and the illuminance and color temperature measured by each sensor and generating the next luminous intensity of each light. If a light affects multiple sensors, neighborhood is determined by the illuminance and color temperature information from the sensor with a higher correlation coefficient (i.e., the nearest sensor).

4 Validation experiment

4.1 Outline of experiment

An intelligent lighting system that controls illuminance and color temperature in an individual and distributed manner is constructed to verify its effectiveness. Fig.5 shows the experiment layout seen from above. The lights used are daylight color fluorescent lamps (4900 K) and warm white color fluorescent lamps (2800 K) with dimmer controls. For target values, sensor A is 950 lx and 3900 K and sensor B is 1050 lx and 3300 K. The number of searches was 400 and the number of trials was five.

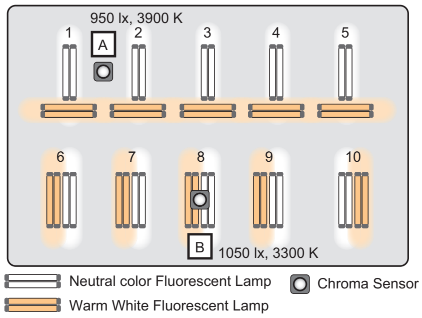


Fig. 5. Experimentation environment

4.2 Result of the experiment

Fig.6 shows the illuminance history. Fig.7 shows the color temperature history. Based on the results of the experiment, the illuminance from the two sensors converged into the target value after approximately 50 steps. The color temperature converged into the target value after approximately 70 searches. Based on these results, the given illuminance and color temperature were controlled in an individual and distributed manner for a given area using the proposed system.

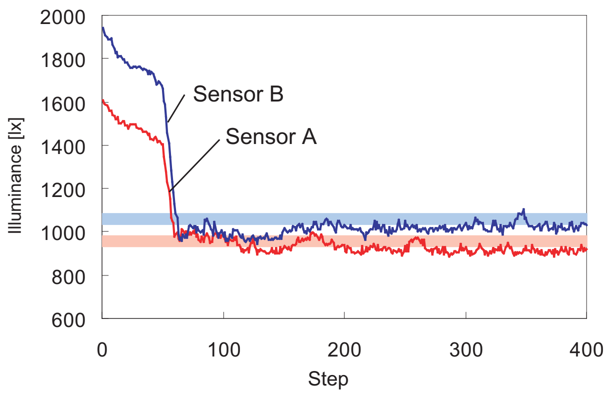


Fig. 6. result of illuminance

5 Conclusion

In this report, an intelligent lighting system that provides individually distributed control of illuminance and color temperature is proposed and constructed. For the optimization algorithm, the effect on the sensors is considered and a method using a neighborhood rule categorizing illuminance and color

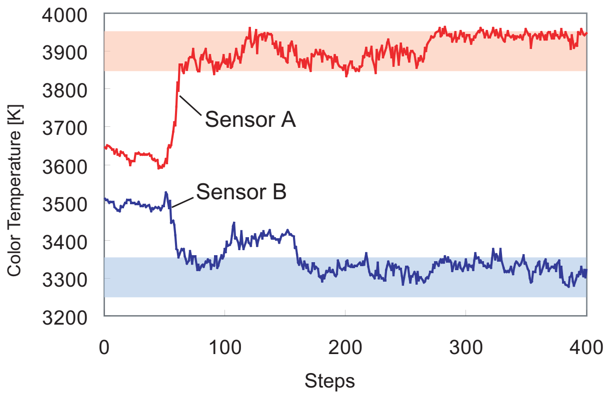


Fig. 7. Result of color temperature

temperature is proposed. The operational experiment shows that the proposed algorithm is effective.

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