Construction of Intelligent Lighting System Using In-office Frames

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***Abstract*—We focus on office lighting environment and conduct a study of Intelligent Lighting System that provides light brightness in accordance to an individual office workers' needs. For purpose of commercialization of this system, Intelligent Lighting System using in-office frame was introduced at Kokuyo Co., Ltd. This place is a special work area used for meetings and discussions, etc. Intelligent Lighting System of LED lighting system that consists of 3 types of colors, such as daylight, warm white and umber was used so that illuminance and color temperature could be controlled. Software for illuminance acquisition, user interface software and software for light control were used as control software. The user interface is web-specified, and illuminance, luminance and color temperature can be designated thereon. In system verification of operability of illuminance and color temperature, illuminance was converged in approximately 100 seconds and color temperature of which difference from target color temperature was within 40Kelvin was provided in areas with little impact of outer light.**

***Keywords*-optimization, intelligent, lighting system, energy saving, office environment**

I. INTRODUCTION

Recently, improvement of office workers' intellectual productivity, creativity and comfortableness has been focused on. There have already been many studies regarding influence of office environment upon intellectual productivity, which report that intellectual productivity is enhanced by improving office environment [1], [2]. In studies focusing on lighting environment among office environment, there are study results which report that required light brightness differs depending on each office worker' s work content and preference [3]. In the future offices, it is assumed to be necessary to create office environment which is appropriate for workers' work contents and individual preferences for purpose of workers' productivity improvement and stress reduction.

In such background, we conduct a study of Intelligent Lighting System that provides light brightness in accordance to individual workers' needs [4]. Intelligent Lighting System enables a user to obtain target illuminance simply by designating illuminance and setting an illuminance sensor on the desk. It consists of lighting equipment, control device, illuminance sensor and power meter, and can provide arbitrary lighting patterns according to a user's request. Effectiveness of Intelligent Lighting System has been verified in the laboratory of Doshisha University [4]. However, actual offices have users of wide range of age groups and the numbers of lightings and users are also larger compared to those of the laboratory. Additionally, durations of experiments have been at maximum 1 month, and therefore, long-term verifications are assumed to be necessary. On the other hand, Kokuyo Co., Ltd. constructs an energy-saving office for verification experiment of eco-office. From above reasons, introduction of Intelligent Lighting System at Kokuyo Co., Ltd. was planned around summer 2008. Doshisha University and Kokuyo Co., Ltd. created a basic design that was completed in November 2008. The constructed Intelligent Lighting System did not use ceiling lights, but it used lighting equipments installed in-office frames. Such Intelligent Lighting System has characteristics of easy installation work as a method to introduce it in an existing building since it can be set without changing ceiling lights. This paper describes details of such system.

II. INTELLIGENT LIGHTING SYSTEM

A. Construction of Intelligent Lighting System

Intelligent Lighting System is a system which provides necessary illuminance and color temperature to necessary places with minimum energy. Intelligent lighting system, as indicated in Fig. 1, is composed of lights equipped with microprocessors, portable illuminance sensors, and electrical power meter, with each element connected via a network.

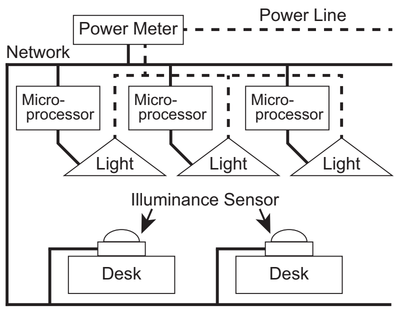

Fig. 1. Configuration of Intelligent Lighting System

B. Control of Intelligent Lighting System

As the best algorithm presently available for lighting control, we have proposed an Adaptive Neighborhood Algorithm using Regression Coefficient (ANA/RC)[5], which was developed by adapting the Stochastic Hill Climbing method (SHC) specifically for lighting control purposes.

In ANA/RC, the design variable is the luminous intensity of each lighting: the algorithm aims to minimize the power consumption while keeping the illuminance at the target level or above. It further enables the control system to learn the effect of each lighting on each illuminance sensor by regression analysis and, by changing the luminous intensity in response, enables a quick transition to the optimum intensity.

The following is the flow of control by ANA/RC:

1) Each lighting lights up by initial luminance.
2) Each illuminance sensor transmits illuminance information (current illuminance, target illuminance) to the network. The electrical power meter transmits power consumption information to the network.
3) Each microprocessor in each lighting acquires the information in step 2), and conducts evaluation of objective function for current luminance.
4) Neighborhood, which is the range of change in luminance based on factor of influence and illuminance information, is selected from seven types shown in Fig. 2.
5) The next luminance within the neighborhood is randomly generated, and the lighting lights up by that luminance.
6) Each illuminance sensor transmits illuminance information to the network. The electrical power meter transmits power consumption information to the network.
7) Each microprocessor in each lighting acquires the information from step 6), and conducts evaluation of objective function for next luminance.
8) The system performs regression analysis based on the luminous intensity data from each lighting and illuminance data from each illuminance sensor to determine the regression coefficient (influence level).
9) If the objective function value is improved, the next luminance is accepted. If this is not the case, the lighting returns to the original luminance.
10) Steps 2) through 9) constitutes one luminous intensity value search operation, which is repeated.

A search operation process (requiring about 2 seconds) consists of steps 2) through 9) above: by iterating this process, the system continues to learn how the lighting affects the illuminance sensor measurement until it realizes the target illuminance with minimum power consumption. Furthermore, by using the influence level found in step 8) as a basis for the evaluation and generation of the next illuminance value, the system can quickly optimize illuminance.

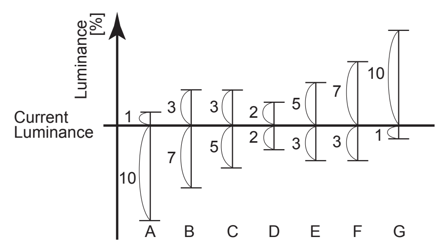

Fig. 2. Seven Types of Neighborhood Design

Next, we will see the objective function used in this algorithm. The purpose of intelligent lighting system is to achieve each user's desired illuminance, and to minimize energy consumption. Thus, it can be understood as an optimization problem in which each lighting optimizes its own luminance. Following from this, the luminance of each lighting is considered a design variable, under the constraint of the user's target illuminance, in resolving the problem of optimization to minimize energy consumption. For this reason, the objective function is set as in Eq. (1).

$$f_i = P + w\sum_{j=1}^{n} g_{ij} \tag{1}$$

$$g_{ij} = \begin{cases} 0 & (Ic_j - It_j) \geq 0 \\ R_{ij} \times (Ic_j - It_j)^2 & (Ic_j - It_j) < 0 \end{cases}$$

$$R_{ij} = \begin{cases} r_{ij} & r_{ij} \geq T \\ 0 & r_{ij} < T \end{cases}$$

i: Index of lightings, j: Index of illuminance sensors
P: Power consumption, w: Weight
Ic: Current illuminance, It: Target illuminance
r: Regression coefficient (influence level)
T: Threashold on influence level

The objective function shown in Eq. (1) is calculated for each lighting. The objective function of each lighting f_i consists of the amount of total electric power P and illuminance constraint g_{ij}. The difference between the current illuminance and target illuminance is used for the constraint g_{ij}, and a penalty is imposed only if the target illuminance is not achieved. As a result, the objective function value largely increases as the target illuminance goes further than the current illuminance. R_{ij} = 0 is multiplied if the influence level r_{ij} is less than the threshold T. With this, if the illuminance sensor with a lower influence level does not achieve the target illuminance, the objective function value does not increase. Therefore, objects for optimization are successfully limited to illuminance sensors to which the lighting gives a strong influence.

Since this intelligent lighting system uses an autonomous distributed-control algorithm, particular cases of installation may use either distributed control or centralized control.

III. Constructed System

A. System Requirements

As explained above, Intelligent Lighting System can set illuminance and color temperature. As a result of discussion with Kokuyo Co., Ltd., the following requirements were suggested for commercialization of Intelligent Lighting System.

1) To provide it not with ceiling lights, but with lighting equipments to be installed on the frame system.
2) To provide it not in general work space, but in a special work area used for meetings, discussions or interviews.
3) To provide certain lighting patterns by controlling illuminance and color temperature so that it becomes suitable for various working styles.
4) To be able to divide areas in order to use it for multiple work activities in the office.
5) To acquire logs for experiment analysis.

Details of the above are described in the following.

B. Provision of Wide-Range Color Temperature

A method to control lighting-up ratio of different color temperatures [6] is used as the color temperature control method. This method, however, can provide values only between color temperatures of each lighting equipment, and therefore, it is necessary to use lighting of high color temperature and that of low color temperature. Thus, this system uses LED lighting system that can provide low color temperature and that can control brightness in the range from 0 to 100 %. In order to provide wide-range color temperature, daylight lighting of color temperature 6100K, light bulb color lighting of color temperature 3400K, and umber lighting of which color temperature is not measurable, but is equivalent to 2000K are used. In the preliminary experiment, it was revealed that users feel discomfort when lightings of 6000K and 2000K were lightened up. Therefore, in this study, daylight and light bulb color are used when color temperature of over 3400K is provided, and light bulb color and umber are used when color temperature of under 3400K is provided. Table.I shows relation between each lighting equipment's luminance ratio and provided color temperature.

Table I
Color Temperature

Color Temperature (K)	Daylight (%)	Warm white (%)	Amber (%)
6000	100	0	0
5500	88	12	0
5000	67	33	0
4500	50	50	0
4000	17	83	0
3500	20	60	20
3000	0	75	25
2500	0	50	50
2000	0	0	100

There is a standard for florescent lamps with light control, and light is controlled by changing duty ratio of PWM signal. The standard for light control signal of LED lighting, however, is not uniformed, and in many cases, it is controlled by either PWM signal or digital signal (DMX or RS485) depending on the lighting equipments. Here, it is controlled by digital signal (RS485) which is controllable with more accuracy. This system is enabled to control each color of LED with 8 bits (256 gradations), which is the same as display's gradation and is possible for sufficient adjustment.

C. Hardware Configuration

As described in the preceding chapter, Intelligent Lighting system can take both distributed control and centralized control as a controlling form. There is not a microprocessor to be embedded in lighting equipment for distributed control at this point and a microcomputer for each lighting equipment is used for distributed control, and therefore, it generates a lot of cost. In this study, system composition of centralized control type is used due to the cost problem. The followings are composition factors

- Frame System
  This system consists of Intelligent Lighting System constructed on frame system of 2.2m high, 3.7m wide and 11.1m deep. The frame system can be divided into 3 areas with partitions. 24 lighting equipments and 6 illuminance sensors are installed in the frame. The number of lighting equipments was determined by the preliminary experiment consideration of the number of lighting equipments with which illuminance is at maximum 1000 lx and which can be individually changed. Furthermore, as for the number of illuminance sensors, although 1 illuminance sensor is used by 1 person in the past Intelligent Lighting System, in this system 1 person does not use 1 sensor, but 2 sensors are installed in 1 area since the frame system is mainly used as a meeting space. Illuminance sensors may be used freely in the area.
- Lighting Equipment
  As mentioned in the preceding paragraph, LED lighting system is used for lighting equipment. Specially ordered LED lighting equipment (Miyachi) is used. Fig. 3

indicates the lighting equipment used for this study. 3 kinds of LED; daylight, warm white and umber are used for lighting equipment. Daylight LED is of high luminance, and others are ordinary LEDs. Daylight is mainly used this time in order to provide maximum 1000 lx on the desk. Lighting luminance is controlled with serial communication (RS485).

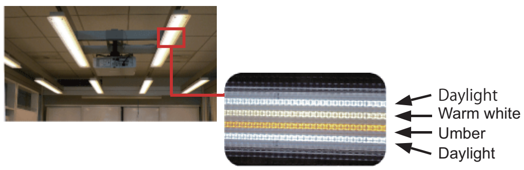

Fig. 3. The LED Light Used in the Office of Kokuyo Co., Ltd.

- Illuminance Sensor
  There are 2 types of illuminance sensors; wired illuminance sensor and wireless illuminance sensor. A wireless illuminance sensor is portable, but it needs battery replacement. In this system, a wired illuminance sensor is used since an illuminance sensor is used only within the frame system and there is no need to use a portable wireless illuminance sensor. "ANA-F11 (Tokyo Koden)" is used. Fig. 4 shows the illuminance sensor used in this study. Illuminance information from the illuminance sensor is outputted in analog signal and it is converted to digital signal through A/D converter to take into system controlling device. An A/D converter (Turtle Industry) with resolution ability of 12 bits is used.

Fig. 4. The Sensor Used in the Office of Kokuyo Co., Ltd.

- System Control Device
  System control device is a general PC embedded with necessary control software.

System is constructed by using the above described devices. Fig. 5 shows system configuration diagram and Fig. 6 shows layout plan of lighting equipments and illuminance sensors respectively. Fig. 6 is a figure of the frame system looked at from above. The control PC is connected to corporate network through firewall, and a user can control lighting by accessing control PC through corporate network from the individual PC.

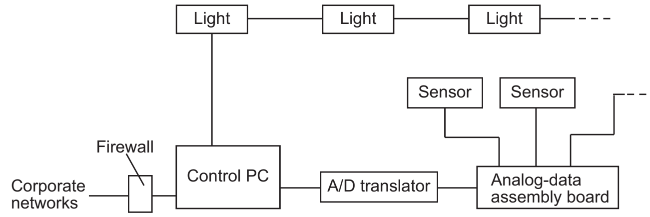

Fig. 5. Configuration of Hardware

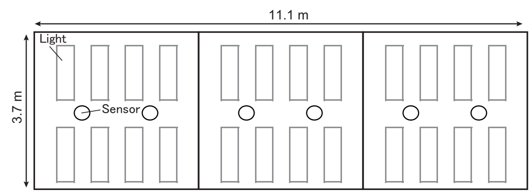

Fig. 6. Location of the Lights and the Sensors (Top View)

D. Software Configuration

This system consists of Software for light control, user interface software and software for illuminance acquisition. User interface is web-specified, and a user can set lighting by accessing the server without installing software in the PC. Software for light control has function to determine lighting luminance using control algorithm based on a user's setup information and send light control signal to lighting equipments and function to write lighting luminance information and color temperature information in hard disk (HD). User interface software has function to write information set on UI screen by a user into HD, and function to acquire illuminance, luminance and color temperature information from HD and display them on the screen. software for illuminance acquisition has function to acquire the current illuminance from illuminance sensors in real time and write it in HD. Fig. 7 shows a diagram of relation of each software. Arrows in the diagram indicate directions of information. The details are as follows.

1) User setup information (setup color temperature and target illuminance)
2) Current illuminance, luminance and color temperature
3) Current illuminance
4) User setup information and current illuminance
5) Luminance and color temperature
6) Light control signal

E. User Interface

User interface with illuminance control is required to be able to confirm the current illuminance of each illuminance sensor and set target illuminance. In order to make these possible, user interface such as Fig. 8 was created.

As a method to select illuminance sensor and input target illuminance value, numerical keypad is displayed on the screen and target illuminance was made possible to be

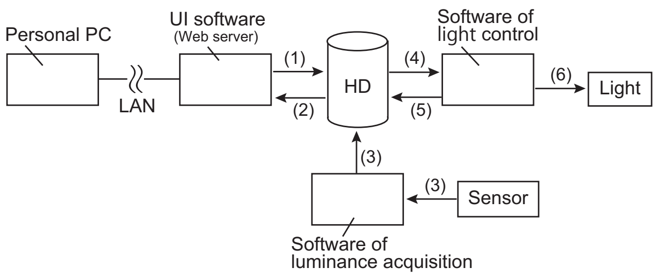

Fig. 7. Configuration of Software

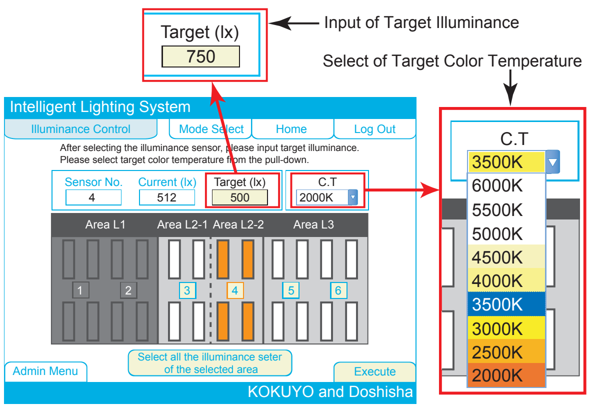

Fig. 8. User Interface for Illuminance Control

inputted. By this, it becomes possible to operate on the touch panel displays installed in each area. On the other hand, lighting color temperature is not controlled by a color meter, but by a method of directly setting color temperature. This is because color meter is expensive. As a method to designate color temperature to lighting equipment, it is desirable to be able to select and set 1 or multiple lightings, but there are 1 illuminance sensor and 4 lightings in the smallest area, so 4 lightings are set each surrounding illuminance sensor. By selecting color temperature from the list of target color temperature, it is possible to set color temperature to the surrounding 4 lights of each illuminance sensor as shown Fig. 8. The list of target color temperature uses Table.I displayed in Paragraph III-B.

F. Application to Frame System

Overview of the constructed system is shown in Fig. 9. Previously, ceiling light replacement work, etc. has been necessary when introducing Intelligent Lighting System. Therefore, introducing it at the existing buildings is not easy because it requires replacement cost, and the building owner's approval is necessary to replace ceiling lights in case of a tenant building. However, application to frame systems has made it possible to introduce Intelligent Lighting System without major facility work. Test lighting can also be used because replacement of lighting equipment in frame systems is easy. Furthermore, measurement of power consumption is easy since its power wiring is independent from ceiling light.

It is possible to create subspace by using partitions and control without intervening each other, and therefore, compatibility between frame systems and Intelligent Lighting System is high.

Fig. 9. Appearance of Intelligent Lighting System

IV. System Verification

A. Realization of Target Illuminance

Verification is conducted to confirm whether the constructed Intelligent Lighting System can provide the requested illuminance. Experiment environment and outer light status are shown in Fig.10. In Experiment A, target illuminance of Illuminance Sensor 1 is set to 500 lx and is changed after 230 seconds. In Experiment B, target illuminances of Illuminance Sensor 1 and 2 are respectively set to 300 and 700 lx. History of illuminance obtained from Experiment A is shown in Fig. 11 and that from Experiment B is shown Fig. 12.

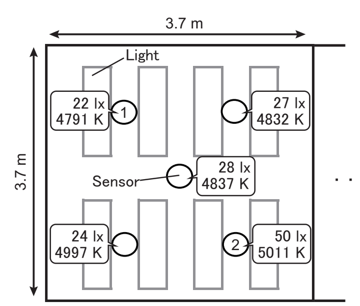

Fig. 10. Experiment Environment (Top view)

Fig. 11 indicates that it converges to the target illuminance and responses to midway change of target illuminance in Experiment A. In Experiment B, although differences in target illuminance of each sensor are far apart, they converged to their target illuminance respectively.

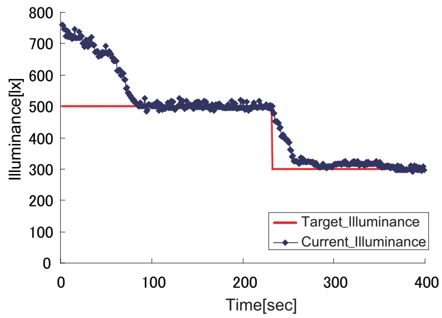

Fig. 11. History of Illuminance (Experiment A)

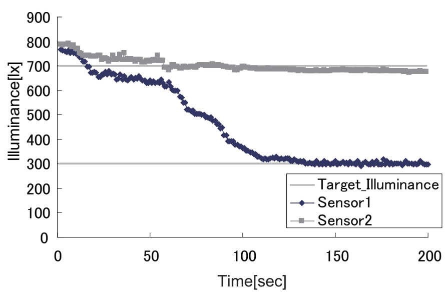

Fig. 12. History of Illuminance (Experiment B)

B. Realization of Target Color Temperature

Verification is conducted to confirm whether the requested color temperature is provided. Experiment environment and outer light status are the same as Fig. 10. Color temperature was measured by color meter "CL-200A" (Konica Minolta). In Experiment C, color temperature of all lightings is set to 2500K and luminance is set to 20 %. Fig. 13 shows illuminance and color temperature distribution obtained from the experiment result.

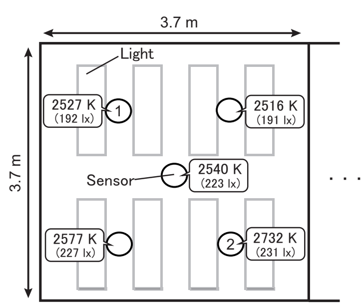

Fig. 13. Distribution of Illuminance and Color Temperature (Top View)

Fig. 13 indicates that measurement position that was influenced by outer light of approximately 5000K had larger difference from target color temperature. The most influenced right-bottom measurement position had as large difference as approximately 230K from target illuminance. In other positions, differences from target color temperature were within 40K.

V. Summary

Intelligent Lighting System can provide target illuminance simply by a user setting such target illuminance on an illuminance sensor and placing the illuminance sensor on the desk. In the aim of commercialization of this system, Intelligent Lighting System that uses corporate frame was introduced at Kokuyo Co., Ltd.

The constructed Intelligent Lighting System is system that uses frame system placed in the office of Kokuyo Co., Ltd. and that can control illuminance and color temperature in special work areas used for meetings and discussions, etc. LED lighting system consisting of 3 types; white, light bulb color and umber was used in order to provide color temperatures of wide range. Wired illuminance sensors were used. Software consists of software for illuminance acquisition, user interface software and Software for light control. The user interface is web-specified, and illuminance, luminance and color temperature can be controlled on the user interface. When possibilities of illuminance and color temperature were investigated in system verification, the requested illuminance could be provided in approximately 100 seconds, and it was provided although target illuminance was changed midway. Also when setting different target illuminances in 2 places, both target illuminances could be provided in approximately 100 seconds. In terms of color temperature, difference from target color temperature in a position with mild outer light was within 40K. In the measurement position that had impact from outer light of approximately 5000K had larger difference from target temperature.

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