Implementation to Provide Individual Illuminance and Color Temperature in an Intelligent Lighting System by Estimating the Color Temperature

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Abstract—We are conducting research and development of the Intelligent Lighting System providing illuminance and color temperature individually to workers at an office. Under the Intelligent Lighting System, a chroma meter is placed on the desktop of each worker in order to measure illuminance and color temperature. It is not easy to introduce the system to a real office, however, as a chroma meter is expensive. This study thus proposes a new method for providing illuminance and color temperature individually to each worker by estimating instead of measuring color temperature. It eliminates the need to use a chroma meter and contributes to enhancing the ease in introducing the Intelligent Lighting System. A verification experiment was conducted to show that illuminance and color temperature can be individually realized at the same precision as when a chroma meter is used.

Keywords: Office, Lighting, Intelligent Lighting System, Color temperature, Chroma meter, Illuminance sensor

1. Introduction

In recent years, there has been increased attention on improvements in the intellectual productivity, creativity, and comfort of office workers within the office environment\[1\]. In the research of Boyce et al., it was reported that providing optimal illuminance separately for each worker is effective from the standpoint of improving the lighting environment\[2\]. Furthermore, when PHILIPS introduced lighting with a color temperature of 17000 K in offices and factories and conducted experiments in relation to this, powers of memory and concentration improved and work efficiency improved\[3\]. In regard to illuminance, it has been reported that preferences differed according to the individual\[4\]. Furthermore, in the same way, it is understood that preferences for color temperature also differ according to the individual\[5\].

It is against such a backdrop that we conduct research on the Intelligent Lighting System that provides illuminance and color temperature individually to each worker at an office\[6\]. The Intelligent Lighting System realizes the illuminance (target illuminance) and color temperature (target color temperature) required by a worker in a location in which a chroma meter is placed at minimal power consumption. This is expected to bring about such effects as improving workers’ comfort and reducing their stress. The system also reduces power consumption by lighting to save more energy in lighting.

The effectiveness of the Intelligent Lighting System has already been recognized, and demonstration tests have been conducted in multiple offices in Tokyo\[7\]. As chroma meters are expensive, Intelligent Lighting Systems introduced into real offices only provided target illuminance by using inexpensive illuminance sensors. Workers manually set color temperature for each lighting fixture through a user interface, which requires their trouble.

We thus devised a method to provide illuminance and color temperature individually to workers without using a chroma meter (simplified method)\[8\]. The simplified method realizes color temperature required by a worker in a simplified manner by lighting lamps around an illuminance sensor at the target color temperature set for the illuminance sensor. In an environment in which illuminance sensors are placed in proximity with each other, however, color temperature required by a worker failed to be realized in some cases.

This study thus proposes a method that provides illuminance and color temperature individually to a worker without using a chroma meter even in an environment in which illuminance sensors are placed in proximity with each other. The proposed method estimates the color temperature of the desktop of each worker from the brightness (luminance) of the lamps and controls the lamps in accordance with the color temperature estimated. This eliminates the need for a chroma meter and improves the extent to which color temperature is realized in comparison with the simplified method. Furthermore, as the operation of setting the color temperature separately for each type of lighting is unnecessary, the burden on the office worker is reduced.

In this study, we construct a system integrating the proposed method, and demonstrate its effectiveness through verification experiments in an environment simulating an actual office. We conduct a verification experiment to show that target illuminance and color temperature can be realized at the same precision as they are realized by a method using a chroma meter. It is also to be shown that the precision for
the target illuminance realized will be improved relative to the simplified method.

2. Intelligent Lighting System

2.1 Construction of Intelligent Lighting System

An Intelligent Lighting System realizes an illuminance level desired by the user while minimizing energy consumption by changing the luminous intensity of lightings. The Intelligent Lighting System, as indicated in Fig.1, is composed of lighting fixtures equipped with lighting control device, chroma meters, and electrical power meters, with each element connected via a network.

The lighting control device evaluates the effectiveness of the current lighting pattern based on the illuminance data and color temperature data from chroma meters and electrical power data from a power meter. By repeating microscopic lighting pattern variations and effectiveness evaluations, the control system tries to minimize power consumption while satisfying the illuminance and color temperature conditions required by each worker.

2.2 Control algorithm of Intelligent Lighting System

Intelligent Lighting System controls use a control algorithm (Adaptive Neighborhood Algorithm using Regression Coefficient: ANA/RC) based on Simulated Annealing (SA)[9]. SA is a general-purpose local search method in which an approximate solution within a range near the current solution is generated and the approximate solution is accepted if the objective function improves. Taking the luminance of the lighting fixture as design variable, it randomly varies the luminance of each lighting fixture in each search to an extent unnoticeable by workers to search an optimum lighting pattern.

Next, we will describe the objective function used in this algorithm. The objective of the Intelligent Lighting System is to achieve the illuminance and color temperatures required by each office worker and minimize power consumption. The objective functions are formalized as shown in Eq. 1.

\[
f_i = P + \omega_i \times \sum_{j=1}^{n} g_{ij} + \omega_c \times \sum_{j=1}^{n} h_{ij}\]

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

\[
h_{ij} = \begin{cases} 
0 & (Cc_j - Ct_j) \geq 0 \\
R_{ij} \times (Cc_j - Ct_j)^2 & (Cc_j - Ct_j) < 0 
\end{cases}
\]

\[
R_{ij} = \begin{cases} 
\rho_{ij} & r_{ij} \geq T \\
0 & r_{ij} < T 
\end{cases}
\]

As indicated in the Eq. 1, the objective function consists of power consumption \(P\) and illuminance constraint \(g_i\) and color temperature constraint \(h_i\). The illuminance constraint \(g_i\) brings current illuminance to target illuminance or greater, as indicated by formula. And color temperature constraint \(h_i\) brings current temperature to target color temperature or greater, as indicated by formula. The influence coefficient \(r_{ij}\) of a Lighting \(i\) on each illuminance sensor \(j\) is a constant.

By conducting a measurement experiment in introducing the system, the influence coefficient \(r\) of each Lighting on each chroma meter is measured.

2.3 Simplified method realizing the target color temperature without using a chroma meter

It is not easy to introduce the Intelligent Lighting System to a real office because chroma meters are expensive. Therefore, Intelligent Lighting Systems introduced into real offices have controlled lighting in accordance with ANA/RC so as to realize the target illuminance only by using only illuminance sensors, which are inexpensive relative to chroma meters. The target color temperature is realized by having workers set color temperature for each lighting fixture through a user interface, which requires their trouble.

We thus devised a method to realize target illuminance and color temperature without using a chroma meter (simplified method)[8]. To realize the target illuminance, the simplified method controls lighting in accordance with ANA/RC, just as Intelligent Lighting Systems introduced in real offices do. It realizes the target color temperature by turning multiple lamps around an illuminance sensor at the target color temperature set for the illuminance sensor. A lamp in a close distance to multiple illuminance sensors is turned on at the average of color temperature values set for those proximate illuminance sensors. Using the simplified method eliminated...
the need for control through a user interface and led to reducing a worker’s burden.

2.4 Problem with color temperature realization under the simplified method

If illuminance sensors are placed in proximity with each other, the simplified method failed to realize the target color temperature in some cases [8]. As workers’ desks are often adjacent to each other in an ordinary office, it is concerned that the target color temperature may not be realized if the simplified method is used. This study thus propose a method that realizes target illuminance and color temperature set by a worker without using a chroma meter even in an environment in which illuminance sensors are in proximity with each other.

3. Method for realizing the target color temperature by estimating the color temperature of the desktop

3.1 Outline of the proposed method

We propose a method for realizing the target illuminance and color temperature for each worker without using a chroma meter. The proposed method estimates the color temperature of the desktop of each worker from information on lamps’ luminance. In accordance with the estimated color temperature and illuminance measured by an illuminance sensor, the target illuminance and color temperature for each worker are realized by using ANA/RC.

3.2 Examination of the method for estimating the color temperature of a desktop

Lighting fixtures used in the Intelligent Lighting System are composed of two types of light sources: natural and warm white light sources. The color temperature of the desktop directly under a single lamp can be estimated from the ratio of illuminance from natural white light sources (natural white illuminance) to illuminance from warm white light sources (warm white illuminance) [8].

A verification experiment was conducted to investigate whether color temperature can be estimated from the ratio of natural white illuminance to warm white illuminance even in an environment in which multiple lamps exist. Fig. 2 shows the experimental environment. Nine LED Lightings made by SHARP were used which can range from 2,700 K to 5,400 K. Three CL-200A chroma meters made by Konica Minolta were used as chroma meters.

The experimental procedure is given below.

1) Randomly determine the luminance of natural and warm white light sources of each lamp.
2) Turn on the natural white light source only at the luminance determined in Step 1) and measure illuminance.
3) Turn on the warm white light source only at the luminance determined in Step 1) and measure illuminance.
4) Turn on both natural and warm white light sources and measure color temperature.

Repeat a trial consisting of Steps 1) through 4). This is intended to verify the relationship between the ratio of natural white illuminance to warm white illuminance and color temperature at each measurement location.

Fig. 3 gives the result of the experiment at the measurement location A. Fig. 3 shows that there is a regular relationship between the ratio of natural white illuminance to warm white illuminance and color temperature in an environment in which multiple lamps exist.

3.3 Method for estimating color temperature on the basis of the luminance of a lamp

Section 3.2 shows that color temperature at an illuminance sensor location can be estimated if natural white illuminance and warm white illuminance at the illuminance sensor location are known. There is a linear relationship between the
illuminance of an illuminance sensor and the luminance of a lamp. Eq. 2 gives the illuminance of an illuminance sensor in an environment in which multiple lamps exist.

\[ I_j = \sum_{i=1}^{N} R_{ij} L_i \]  

\( i \): lamp ID, \( j \): sensor ID, \( N \): number of lightings 
\( I_j \): illuminance from sensor \( j \) [lx] 
\( L_i \): luminance of lamp \( i \) [cd] 
\( R \): influence coefficient for illuminance sensor \( j \) for lamp \( i \) [lx/cd]

Therefore, by using influence coefficient \( R \), the natural white illuminance and the warm white illuminance at each illuminance sensor location can be calculated from the luminance of lamps.

Under the proposed method, the experiment in Section 3.2 is to be conducted in advance. A regression curve was derived from data obtained by using the least square method, and the polynomial in the function of the regression curve was defined as the model equation for the color temperature estimation at that location. Using the model equation, color temperature is estimated from the ratio of natural white illuminance to warm white illuminance calculated in accordance with Eq. 2. Color temperature is thus estimated from the luminance of lamps instead of being measured by using a chroma meter, and lighting is controlled using ANA/RC.

4. Verification experiments

4.1 Outline of the verification experiments

Following two verification experiments were conducted to demonstrate the effectiveness of the proposed method.

- Verification experiment for color temperature estimating precision
- Verification experiment for the extent of color temperature realization by the Intelligent Lighting System incorporating the proposed method

Fig. 4 shows the experimental environment. The laboratory, lamps, and chroma meter used in the experiment are the same as those for the experiment in Section 3.2. The influence coefficient of each lamp on each influence sensor was measured in advance. Since a difference in color temperatures is not in a proportional relation with that in colors recognized by human eyes, an inverse color temperature, which is the inverse of a color temperature, was used for verification. An inverse color temperature is the inverse of a color temperature multiplied by \( 10^6 \) and represented in the unit of mired \((K^{-1})\).

4.2 Verification of color temperature estimating precision

The luminance of each lamp was changed 500 times at random, and the color temperature at the location where each chroma meter was placed was estimated using the proposed method each time luminance was changed. The difference between an estimated color temperature and a corresponding measured color temperature was calculated to be used as an error to evaluate the proposed method. The model equation for estimating a color temperature by the proposed method at each measurement location was derived in advance by conducting the experiment described in Section 3.2.

Fig. 5 shows the histogram of color temperature error at the chroma meter A. In Fig. 5, the average inverse color temperature error was 1.11 \( K^{-1} \), and the maximum inverse color temperature error was 5.04 \( K^{-1} \). At the chroma meter B, the average inverse color error was 0.97 \( K^{-1} \), and the maximum inverse color temperature error was 5.41 \( K^{-1} \), exhibiting the largest color temperature errors among all chroma meters. At the chroma meter C, the average inverse color error was 1.03 \( K^{-1} \), and the maximum inverse color temperature error was 4.52 \( K^{-1} \), exhibiting the smallest color temperature errors among all chroma meters. Regarding color temperature, it is known that a difference in inverse color temperature of about 5.5 \( K^{-1} \) is not recognized by human eyes. Since the maximum inverse color temperature difference is 5.5 \( K^{-1} \) or less at any chroma meter, those errors are considered to be sufficiently small.
4.3 Verification of the extent of illuminance and color temperature realization

The extent of illuminance and color temperature realization was verified to show the effectiveness of the Intelligent Lighting System incorporating the proposed method. In the initial condition, all lamps were turned on at the maximum lighting luminance, and the Intelligent Lighting System was started under that condition. The target illuminance and color temperature at chroma meters A, B, and C were set to 600 lx and 5000 K, 400 lx and 3000 K, and 500 lx and 4000 K, respectively.

The Intelligent Lighting System was operated for 1,000 steps (about 2,000 seconds) using the conventional method using chroma meters, the simplified method, and the proposed method. Under the simplified and proposed methods, color temperatures obtained from chroma meters were used only to confirm the extent of realization and not to control lighting.

Fig. 6 shows lamp lighting patterns 2,000 seconds after the start of the experiment. It is found that lamps near a chroma meter were brightly turned on, realizing an energy saving lighting pattern. Fig. 6-(b) also shows that lamps in a close distance to a chroma meter were turned on at the target color temperature set for that chroma meter. Fig. 6-(a) and Fig. 6-(c) show that color temperatures of lamps were finely controlled in order to realize target color temperatures.

Histories of illuminance under the conventional, simplified, and proposed methods are given, respectively, in Fig. 7, Fig. 8, and Fig. 9. In each history of illuminance, let us focus on the period from 1,600 seconds to 2,000 seconds after the start of the experiment, when lighting control stabilized. In Fig. 7, the average error from the target illuminance was 16 lx, 11 lx, and 13 lx, respectively, at the chroma meter A, B, and C. Next, in Fig. 8, the average error from the target illuminance was, respectively, 11 lx, 9 lx, and 10 lx. Next, in Fig. 9, the average error from the target illuminance was, respectively, 8 lx, 5 lx, and 7 lx. It is known that, when a worker is working at VDT, a difference in illuminance of about 12% is not recognized by human eyes. An error is considered to be sufficiently small at chroma meter A, B, and C if it is, respectively, 72 lx or less, 48 lx or less, and 60 lx or less. Consequently, as a result, values of luminance measured by each chroma meter under each method satisfied this condition.

Next, histories of color temperature under the conven-
tional, simplified, and proposed methods are given, respectively, in Fig. 10, Fig. 11, and Fig. 12. In each history of color temperature, let us focus on the period from 1,600 seconds to 2,000 seconds after the start of the experiment, when lighting control stabilized. In Fig. 10, the average error from the target color temperature was 22 K, 15 K, and 23 K, respectively, at the chroma meter A, B, and C. Next, in Fig. 11, the average error from the target color temperature was, respectively, 263 K, 113 K, and 312 K. On the other hand, in Fig. 12, the average error from the target color temperature was, respectively, 41 K, 20 K, and 15 K. It is known that a difference in color temperature of about 5.5 K is not recognized by human eyes. An error is considered to be sufficiently small at chroma meter A, B, and C if it is, respectively 138 K or less, 50 K or less, and 88 K or less. As a result, values of luminance measured by every illuminance meter under the conventional and proposed methods satisfied this condition. On the other hand, under the simplified method, no illuminance sensor was able to satisfy this condition. Based on the above result, it can be said that, even in an environment in which chroma meters are in proximity with each other, the approach for realizing color temperature using the proposed method is effective compared with the simplified method.

5. Conclusion

In this study, we the proposed method to realize target illuminance and target color temperature required by each worker without using a chroma meter. We conducted verification experiment, and we showed that there is a regular relationship between the ratio of natural white illuminance to warm white illuminance and color temperature. Therefore, in the proposed method, color temperature of a desktop is estimated from the ratio of natural white illuminance to warm white illuminance. A verification experiment was conducted to show that illuminance and color temperature can be individually realized at the same precision as they are realized by a method using a chroma meter. Using this method, the chroma meter is unnecessary and the operation of setting the color temperature of each light separately is also not required. From these points, we can expect that by integrating the proposed method into the Intelligent Lighting System, individual illuminance and color temperature can be provided to each office worker.

References
