Implementation to Provide Individual Illuminance and Color Temperature in an Intelligent Lighting System without Chroma Meter

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Abstract—The authors have conducted research into an Intelligent Lighting System in order to achieve the illuminance and color temperature levels required by each office worker with low power consumption through the use of a chroma meter. However, as these chroma meters are very expensive, it is not easy to introduce them into offices. For this reason, we have proposed a new method for an Intelligent Lighting System that achieves separate color illuminance and color temperature for the specified location, without using a chroma meter. In verification experiments demonstrating the effectiveness of the proposed method, we have performed comparative experiments between methods using chroma meters and the proposed method. It was possible to achieve the illuminance/color temperature required by each office worker, when the illuminance sensors are separated by more than twice the lighting placement interval.

Keywords: Office, Lighting control, Intelligent Lighting System, Optimization, Color temperature, Chroma meter, Illuminance sensors

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 \cite{1,2}. 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 \cite{3}. 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 \cite{4}.

In regard to illuminance, it has been reported that preferences differed according to the individual \cite{5}. Furthermore, in the same way, it is understood that preferences for color temperature also differ according to the individual \cite{6}.

For this reason, the authors have concentrated on the lighting environment in offices, and proposed an Intelligent Lighting System that provides illuminance and color temperature based on the individual request of the office worker \cite{7}. With the Intelligent Lighting System, as the office worker sets the required illuminance (target illuminance) and required color temperature (target color temperature) using a chroma meter that can measure the illuminance and color temperature, it is possible to achieve lighting patterns that reach this value with the minimum amount of power.

The effectiveness of the Intelligent Lighting System has already been recognized, and verification experiments have been conducted in multiple offices within the Tokyo Metropolitan District \cite{8,9}. Due to the fact that chroma meters are expensive, the Intelligent Lighting Systems introduced in actual offices are controlled using only illuminance sensors. Here, illuminance is controlled automatically, and color temperature controls are performed manually for each lighting incidence, so this is considered troublesome for the office workers.

By illuminance for the specified location, without using chroma meters. In this way, it is possible to achieve the illuminance and color temperature required by the office worker without using chroma meters. 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.

2. Intelligent Lighting System

2.1 Overview of an Intelligent Lighting System

The Intelligent Lighting System is a lighting system that provides the illuminance and color temperature required by the office worker in the specified location with low power consumption \cite{7}. In this structure, multiple lighting devices capable of light control, multiple chroma meters, a control device, and a wattmeter are connected together in a single network. The structure of the Intelligent Lighting System is shown in Fig.1.

The control device set for each lighting incidence changes the luminous intensity based on the illuminance information and color temperature obtained from the chroma meter.
and the power consumption information obtained from the wattmeter, using the optimization method. Through the repetition of this process, it can achieve the illuminance and color temperature required by the office worker. In addition, the Intelligent Lighting System does not require physical location information from the chroma meter. This is because it learns the influence ratio (illuminance/luminous intensity) illuminance/luminous intensity influence ratio) of the lighting on the chroma meter from the illuminance information obtained from each of the chroma meters and luminous intensity information obtained from each lighting incidence.

2.2 Control algorithm using regression analysis

Intelligent Lighting System controls use a control algorithm (Adaptive Neighborhood Algorithm using Regression Coefficient: ANA/RC) based on Simulated Annealing (SA) [10]. ANA/RC uses the luminous intensity of each lighting as a design variable and changes the luminous intensity in each lighting per search at random within a range [11] not detectable by the office worker to search for the optimal lighting pattern. The minimum power consumption is then sought under the conditions of illuminance and target illuminance/color temperature required by the office worker and minimize power consumption. The objective functions are formalized as shown in formula (1).

$$f_i = P + \omega_l \times \sum_{j=1}^{n} g_{ij} + \omega_c \times \sum_{j=1}^{n} h_{ij}$$ (1)

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

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

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

$i$: number of lightings, $j$: number of sensors

$$\omega_l: \text{weight [Wlx^2]}, \omega_c: \text{weight [W/K]}$$

$P$: power consumption [W], $Ic$: current illuminance [lx], $It$: target illuminance [lx], $Cc$: current color temperature [K], $Ct$: target color temperature [K], $L$: luminance [cd]

$T$: threshold

$r_{ij}$: Regression coefficient for illuminance sensor $j$ for illumination $i$

The objective function shown in formula (1) is comprised of power consumption $P$, illuminance restriction $g_{ij}$ and color temperature restriction $h_{ij}$, and is calculated for each lighting incidence. As the penalty function $g_{ij}$ and $h_{ij}$, which are restrictive conditions for target illuminance, and the target color temperature for the chroma meter fluctuate more than the regression coefficient $r_{ij}$, the penalty functions are increasingly minimized the larger the regression coefficient of the lighting. Furthermore, by setting the threshold $T$ for regression coefficient $r_{ij}$, the target for optimization can be filtered to the lighting, which strongly influences the chroma meter. In this way, the lighting that is distant from the chroma meter is only operated for the purpose of minimizing power consumption.

3. Lighting control method for achieving target color temperature in the specified location without using a chroma meter

3.1 Structure of the proposed method

As described above, due to the fact that the chroma meters are expensive, it is not easy to introduce them into offices. For this reason, this study presents a method of achieving the illumination/color temperature required in the specified locations, using only illuminance sensors. The proposed method extracts lighting close to the illuminance sensors based on the illuminance/luminous intensity influence level, and lights these to the target color temperature. Furthermore,
where the extracted lighting is lighting with a high illuminance/luminous intensity influence level in relation to the illuminance sensor, it is lit to the average mired value for that color temperature. The mired value is a value expressing the reciprocal of the color temperature, and has a proportional relationship with human visual color perception; this makes it possible to express the differences in color temperature between different color temperatures.

### 3.2 Method of lighting to the specified color temperature

A method for controlling the lighting ratio is used as a way to light each lighting incidence to the specified color temperature. By lighting to colors with two different color temperatures, and changing this lighting ratio, it is possible to achieve color temperatures across a wide range. For this reason, the lighting ratio of the two lighting colors for achieving the target color temperature is sought experimentally, and the relationship between the lighting ratio for neutral white and incandescent lighting and the color temperature is stored within the system as a table. Then, when lighting to the light at the specified color temperature, the light is lit at the ratio obtained from the color temperature table.

#### Table 1: Lighting ratio of neutral and incandescent lightings

<table>
<thead>
<tr>
<th>Color Temperature [K]</th>
<th>Neutral Lighting [%]</th>
<th>Incandescent Lighting [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2700</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>3000</td>
<td>21</td>
<td>79</td>
</tr>
<tr>
<td>3300</td>
<td>67</td>
<td>33</td>
</tr>
<tr>
<td>3600</td>
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<td>53</td>
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<td>3900</td>
<td>57</td>
<td>43</td>
</tr>
<tr>
<td>4200</td>
<td>67</td>
<td>33</td>
</tr>
<tr>
<td>4500</td>
<td>76</td>
<td>24</td>
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<tr>
<td>4800</td>
<td>84</td>
<td>16</td>
</tr>
<tr>
<td>5100</td>
<td>91</td>
<td>9</td>
</tr>
<tr>
<td>5400</td>
<td>100</td>
<td>0</td>
</tr>
</tbody>
</table>

### 3.3 Method of extracting lighting close to illuminance sensors using a lighting layout plan

With the Intelligent Lighting System, when estimating the illuminance/oxygen intensity level of influence, the two lights with the most significant influence on the illuminance sensor can be specified based on the size of the regression coefficient. However, as the regression coefficients of other lights have a large degree of error, there are times when the estimated degree of error may occur \[12\]. With the proposed method, by using the two lights with the largest regression coefficients and the layout plan, the light closest to the illuminance can be accurately extracted.

Fig.2 is a concept diagram of the method described above. As shown in Fig.2, by placing one illuminance sensor unit, the two lights (lights 2 and 3) with the highest illuminance/oxygen intensity influence level are determined through regression analysis, and these are considered to be adjacent lightings. The lightings that influence this illuminance sensor are estimated to exist near the adjacent lighting. Next, the lighting near the adjacent lighting is extracted using the lighting layout plan. Here, the direct line distance from the adjacent lighting to each lighting incidence is calculated, and the lighting close to either adjacent lighting is sought. As the direct line distance on the diagonal line is the maximum distance between the lighting, distances below this distance can be considered to be close lighting. Therefore, in the case of the environment shown in Fig.2, the lighting group (lighting 2, lighting 1, 3, 4, 5, 6, and lighting 3, lighting 2, 5, 6) with a close straight line distance to the adjacent lighting can be extracted. Thereupon, by taking the intersection of the lighting groups extracted from the lighting layout plan, the closest lighting to any of the adjacent lighting (lighting 2, 3) and adjacent lighting (lighting 5 and 6) can be extracted, and this is the adjacent lighting. The extracted adjacent lighting are the lighting close to the illuminance sensor.

### 3.4 Proposed control method

The flow of color temperature control in the proposed method is as follows. As a maximum of six lights can influence the illuminance sensor, the upper 4 - 6 lights with the greatest illuminance/oxygen intensity to the sensors are lit to the target color temperature.

1) Regression analysis is carried out based on the illuminance and oxygen intensity, and the illuminance/oxygen intensity influence level is calculated.

2) The adjacent lighting close to the illuminance sensors are extracted using the illuminance/oxygen intensity level of influence.

![Figure 2: Concept of lighting estimation method](image)
We confirmed from Fig.6, which shows the light patterns for the method using the chroma meter that the color temperature is different for each lighting incidence when using the chroma meter. This is because a control is performed using a method of optimization based on the information obtained from the chroma meter in order to satisfy the required color temperature. In contrast, in Fig.7 that shows the light patterns in the proposed method, it lights according to the target color temperature of the illuminance sensor corresponding to the adjacent lighting near the Illuminance sensor. Furthermore, we calculated the average mired value for the illuminance sensor corresponding to the adjacent lighting and confirmed that it is lit at that color temperature.
4.3 Verification when the illuminance sensor is neighbor

We verified the various lighting situations where illuminance sensors A and B were located within 1.8 m of each other as shown in Fig.3-(b). Furthermore, the history of illuminance and color temperature for the method where the chroma meter is used and the proposed method where the chroma meter is not used are shown in Fig.8 and 9. The light luminous intensity and color temperature after running for 600 seconds for each method is shown in Fig.10 and 11.

Fig.3-(b), sensor C is separated from the other illuminance sensors, when the illuminance sensors are neighboring. In this way, as in Fig.5, we confirmed that the proposed method can be implemented within ± 150 K of the target color temperature. Furthermore, in the proposed method for sensor A, it can be implemented within ± 150 K of the target color temperature, as well. On the other hand, it can be confirmed from Fig.5 that as sensor A is neighboring to sensor B, the sensor A target temperature is interfering with sensor B. As in the proposed method, lighting control is performed without obtaining color temperature information, and the result is that the target color temperature for sensors A and B affect each other.

Based on the above, we confirmed that when the illuminance sensors are adjacent and at a distance of within 1.8 m, it is possible to approach the target color temperatures for each sensor using the proposed method, but that the implementability of the color temperature is poorer than that in the previous section.

5. Conclusion

In this study, we have proposed a method, through the Intelligent Lighting System, of achieving the illuminance and color temperature levels required by each office worker without using a chroma meter. Based on the verification results, we see that when illuminance sensors are located at the same distance as the lighting placement interval, the color temperatures for the neighboring illuminance sensors interfered with each other. In contrast, when the illuminance sensors are located at approximately twice or more the lighting placement intervals, it was possible to achieve the illuminance and color temperature required by the individual office workers. 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 an Intelligent Lighting System, individual illuminance and color temperature can be provided to each office worker.

References