Distributed Autonomous Lighting Optimization Algorithm using Regression Coefficient

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Abstract

An individual lighting control per individual worker improves intellectual productivity and reduces power consumption, therefore, the algorithm to efficiently control individual lighting is important. We have proposed the distributed lighting control system using an optimization algorithm that provides individual luminance to the specified locations. We call this method "the Adaptive Neighborhood Algorithm using Correlation Coefficient (ANA/CC)". The lighting system consumes more than 20% of the total energy in office buildings, and ANA/CC could reduce energy consumption from 30 to 50%. However, from demonstration experiments, we found it was difficult to estimate the influence of the luminance and room illuminance directly using the correlation coefficient. Therefore, we propose the new lighting control algorithm that estimates precisely the factor of the influence of the luminance and room illuminance by using the regression analysis, and show the effectiveness of this algorithm.

Keywords: Optimization, Distributed Algorithm, Distributed Illuminance Control, Enegy-Saving

1 INTRODUCTION

In office space, a desktop illuminance of 750lx and color temperature of 5000K is commonly used for light in Japan, while it has been reported that an individual illuminance control per individual worker improves intellectual productivity and reduces power consumption [1-3]. The lighting system occupies approximately 20% of total energy consumption of a whole building [4], and individual control of lighting is important from the viewpoint of the reduction of power consumption [5-6]. Therefore, we have been researching and developing lighting algorithms to individually provide illuminance preferred by each office worker by using ceiling lights[7-9]. It is important to determine the closer luminance pattern to the each user's desired illuminance level to minimize electrical power usage by using the optimization algorithm for an individual lighting control. We have proposed Adaptive Neighborhood Algorithm using Correlation Coefficient (ANA/CC)[10] as the optimization algorithm for luminance control, and its effectiveness has been verified. With this algorithm, the approximate position relation between the light and the illuminance sensor is calculated with a correlation coefficient based on the changes in the luminance and room illuminance. The appropriate luminance is generated according to this value, so that convergence into the target illuminance is achieved within a short time. However, ANA/CC could not get the direct consequence between the luminance and room illuminance.

In this paper, we propose the algorithm that determines the position relation between the light and the illuminance sensor by using a regression analysis for their accurate position relation based on change in the luminance and room illuminance, verify the effectiveness of the proposed algorithm.

2 DETERMINATION OF THE POSITION RELATION BETWEEN LIGHTS AND ILLUMINANCE SENSOR

It is important to determinate the position relation between the light and the illuminance sensor to satisfy the target illuminance and achieve the power-saving condition. Fig.1 shows the location of the lights and the illumiance sensors. Suppose that the target illuminance value of Sensor1 is 110lx, Light1 provides luminance equivalent to 30lx and Light2 provides luminance equivalent to 80lx. Under this condition, the target illuminance is achieved by the distant light. When the position relation between the light and the illuminance sensor is unknown, it is possible to converge into this kind of lighting pattern. However, if the position relation between the light and the illuminance sensor can be determined, the lighting pattern could be determined below the arrow. This pattern is more effective to satisfy the target illuminance 110lx. Thus, by determining the position relation between the light and the illuminance sensor, the effective lighting pattern from the viewpoint of energy conservation could be determined. Therefore, it is very important to determine the accurate position relation between the light and the illuminance sensor.

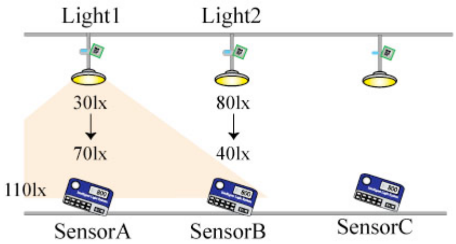
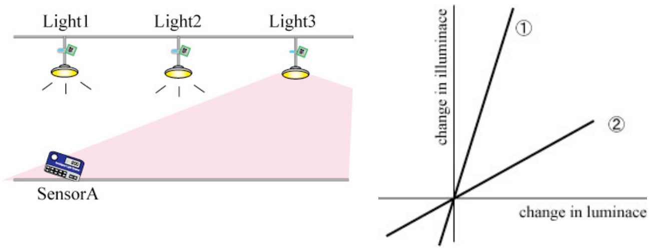


Fig.1 Location of lights and illuminance sensors

2.1 DETERMINATION OF POSITION RELATION USING CORRELATION COEFFICIENT

The Adaptive Neighborhood Algorithm using Correlation Coefficient (ANA/CC)[10] has been proposed to obtain a correlation coefficient between the change in luminance of the light and the change in illuminance of the illuminance sensor. With ANA/CC, the position relation between the light and the illuminance sensor is determined based on the strength of correlation and the variation range of luminance of light. The luminance of light is adaptively changed depending on the correlation, to improve the effectiveness of convergence into the target illuminance. This method showed high performance compared with the method to randomly change the light pattern without using the relationship between the light and the illuminance sensor. However, only the linear relationship is measured with the correlation coefficient, which might not be accurately determined in some case.

Fig.2 shows the example where the position relation is not successfully obtained with correlation. In the case that light 1 strongly illuminate and other lights turn off or illuminate with very small luminance under the environment of Fig.2(a), the change in the illuminance sensor to the change in luminance of light increase like the straight line of 1 in Fig.2(b), and the gradient increase. On the other hand, in the case that Light 3 strongly illuminate and other lights turn off or illuminate with very small luminance, the gradient decreases in comparison with 1, as shown with the straight line of 2. However, the correlation coefficient is only influenced by the strongly illuminated light; therefore values close to 1 are obtained in both case. Since the correlation coefficient only measures the difference between the change in luminance of the light and the change in illuminance of the illuminance sensor, the distance cannot be accurately measured as indicated in the above example; therefore if the correlation coefficient is used, it might not be possible to accurately determined position relations.



(a) environment (b)gradient

Fig.2 Problem with correlation coefficient

3 ADAPTIVE NEIGHBORHOOD ALGORITHM USING REGRESSION COEFFICIENT

In the previous section, we showed the position relation between the light and the illuminance sensor might not be accurately obtained with correlation coefficient. However, it was found that accurate position relations between the light and the illuminance sensor can be determined by using the gradient of the change in luminance of the light to the change in illuminance of the illuminance sensor. Thus, we describe about obtaining an approximate relation between these two variables by using gradient.

In this paper, we propose the Adaptive Neighborhood Algorithm using Regression Coefficient (ANA/RC) as the improved method of ANA/CC. With this algorithm, the regression coefficient is estimated with the sequential least squares method based on the changes in luminance of the light and in illuminance obtained from the illuminance sensor, and the variation range (hereafter the neighborhood range) of luminance is adaptively calculated based on the regression coefficient. The influence rate is defined by

$$y_i = \beta_0 + \beta_1 x_i , \quad (1)$$

where x is the amount of change in luminance (explanatory variable) and y is the amount of change in illuminance (observed value y). The algorithm of ANA/RC is explained as follows.

(1) Illuminate each light at initial luminance and set the target illuminance for each illuminance sensor.
(2) Each light gets illuminance value and the value of power consumption to evaluate the objective function value.
(3) Each light determines the optimum neighborhood range from sensor information and regression coefficient.
(4) Generate the next step's luminance within the neighborhood range.
(5) The regression coefficient is determined from the luminance and illuminance values at each light.
(6) Evaluate the objective function value of the next step. If the value of the objective function is improved, adopt the luminance value, return to 2 and repeat steps.
(7) If the value of the objective function is not improved in 6, set the luminance value at the previous step and repeat steps.
The objective function is defined by

$$f_i = P + w\sum_{j=1}^{n} g_{ij} \quad i = 1, 2, 3, .., m$$

$$g_{ij} = \begin{cases} 0 & (Lc_j - Lt_j \geq 0) \\ \gamma_{ij}(Lc_j - Lt_j)^2 & (Lc_j - Lt_j < 0) \end{cases} , \quad (2)$$

where n is the number of illuminance sensors and m is the number of lights and P is the amount of power consumption and Lc is current illuminance and Lt is target illuminance and w is weighting factor and $\gamma_{i,j}$ is the influence on light i in regards to illuminance sensor j, for i=1,...,m.

The objective is to minimize the function f_i with luminance of light. f_i consists of g_i represented the difference of illuminance between the current illuminance L_C and the target illuminance L_t as well as power consumption P. g_i is added when the difference of illuminance is negative, i.e., the current illuminance is lower than the target illuminance, The power consumption P is obtained from a power meter. The neighborhood range is defined as follows:

$$\begin{cases} A(\text{dimming N}) & r_j < threshold \\ B & r_j \geq threshold \quad and \quad Lt_j \leq Lc_j \\ C(\text{brightening N}) & r_j \geq threshold \quad and \quad Lt_j > Lc_j \end{cases} ,$$

where N is neighborhood and r_j is regression coefficient of illuminance sensor j and A-C is neighborhood type.

When the regression coefficient is higher than the threshold and the current illuminance is lower than the target illuminance, the brightening neighborhood C is set and the light brightens gradually. When the regression coefficient is lower than the threshold, the position relation between light and illuminance sensor is determined to be distant. The dimming neighborhood A is set and the light dims gradually. When the regression coefficient is higher than the threshold and the current illuminance is higher than the target illuminance, it could be considered that the required illuminance is achieved although the position relation between light and illuminance sensor is near. The luminance is changed within the current neighborhood range.

In this way, when the position relation between the light and the illuminance sensor is near and the target illuminance is not satisfied, the light illuminates within the current neighborhood range. The position relation is near but the target illuminance is satisfied. The light dims if the light and illuminance sensor is distantly positioned. By adaptively changing the neighborhood range of luminance based on the regression coefficient, the luminance is autonomously changed, and the target illuminance is achieved and the lighting pattern with low power consumption is automatically obtained successfully. While the position relation is determined by using the threshold in the case of the algorithm, it is determined by a preliminary experiment in this case.

For regression analysis, the sequential least squares method is used with the Kalman filter to enable highly accurate estimation [11,12]. The regression coefficient is recursively estimated with the sequential least squares method. The regression coefficient β is estimated with the following procedures. In this case, k indicates the current step. The initial estimated values for $\hat{\beta}(k\text{-}1)$ and $P(k\text{-}1)$ are given.

(1) Evaluate covariance of predicted observation error $S(k)$,
$S(k) = x(k)P(k\text{-}1)x(k)^T + R(k)$.
(2) Evaluete the Kalman filter $W(k)$,
$W(k) = P(k\text{-}1)x(k)^T S^{-1}(k)$.
(3) Evaluate covariance of estimated error $P(k)$,
$P(k) = P(k\text{-}1) - W(k)x(k)P(k\text{-}1)$.
(4) Evaluate predicted observation value $\hat{y}$,
$\hat{y}(k) = x(k)\hat{\beta}(k\text{-}1)$.
(5) Evalutate predicted observation error $\varepsilon(k)$,
$\varepsilon(k) = y(k) - \hat{y}(k)$.
(6) Evaluate estimated value $\hat{\beta}(k)$,
$\hat{\beta}(k) = \hat{\beta}(k\text{-}1) + W(k)\varepsilon(k)$.

By repeating steps 1 to 6, the estimated value β_1 that minimizes the predicted observation error in the change in illuminance is estimated based on the change in luminance. β_1 is the gradient of the regression, and β_1 is the coefficient that explains the relationship between the change in luminance and the change in illuminance. Thus, the greatness of β_1 represents the sensitivity of between the change in illuminance of each illuminance sensor and the change in luminance of light, and could be defined as the position relation between the light and the illuminance sensor. $R(k)$ is the covariance of measured noise w, and used to weight for the measured value y. If the covariance of measured noise w is small, $R(k)$ is set to be larger. The covariance of measured observation error $S(k)$ and the Kalman filter W also have the role of weight in the same way, so if the measured error $\varepsilon(k)$ increases, $S(k)$ and W also increases.

4 EXPERIMENTAL EVOLUTION

4.1 EXPERIMENTAL SETTING

We now describe the experimental setting. First, we evaluated the performance of the position relation using regression coefficient between illuminace sensors and lights under the environment of Fig.1.

Next, using an actual space, we evaluated the effectiveness of the proposed method by increasing the number of lights and illuminance sensors. The position relation of the experimental apparatus is indicated in Fig.4. The experimental laboratory has system ceiling, and 30 fluorescent lights for system ceiling are installed. Since the illuminance value becomes very high if all lights are in use, half of them (15 lights) were used at this time, as indicated in the figure. Three illuminance sensors were used, and their movement is indicated with arrows in the figure (e.g., the movement from Light 5 to Light 10). Table1 shows the parameters.

The experiment is performed under the following environment to evaluate performance of ANA/RC. We evaluated the convergence ability and confirmed the correlation coefficient under three environments. We compared with ANA/CC and ANA/RC.

Table1 Parameters

parameter	value
target illuminance	800,700,600
threshold	0.08

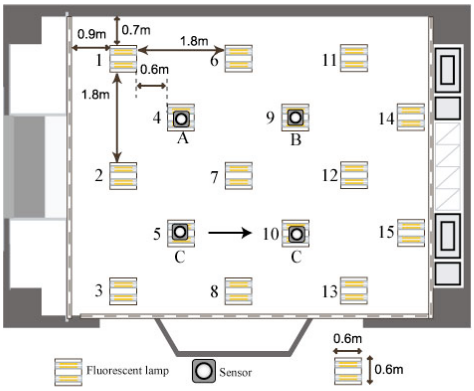


Fig.4 Experimental Environment

(1) The environment is stable. (not changed)

Target illuminance values of illuminance sensors are set at 600lx for sensor A, 700lx for sensor B and 800lx for sensor C, respectively. The positions to set up sensors are indicated in Fig.4.

(2) The target illuminance is changed.

After the static condition is reached under the (1) environment, the target illuminance for illuminance sensor A is changed from 600lx to 750lx.

(3) The illuminance sensor is moved.

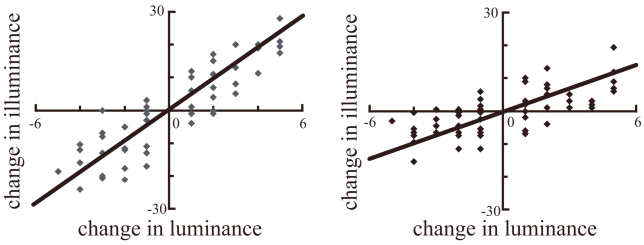
After the static condition is reached under the (1) environment, illuminance sensor C is moved right under Light 10. The arrow in Fig.4 indicates the position after the move.

4.2 REGRESSION COEFFICIENT

When Light 1 is randomly illuminated under the environment of Fig.1, we evaluated the relation accuracy by observed the values of regression coefficient of sensor A and B. The results are indicated in Fig.3.

The relationship between the change in illuminance of the sensor and the change in luminance of the light is represented by dot, and the line shows the regression line. The x-axis in Fig.3 represents the change in luminance and the y-axis represents the change in illuminance.

From these results, it is found that the difference between the change in luminance of light and the change in illuminance of illuminance sensor A is a similar level compared to illuminance sensor B. The gradient of sensor A is greater than sensor B, so it could be said that the correct positions could be determined successfully.



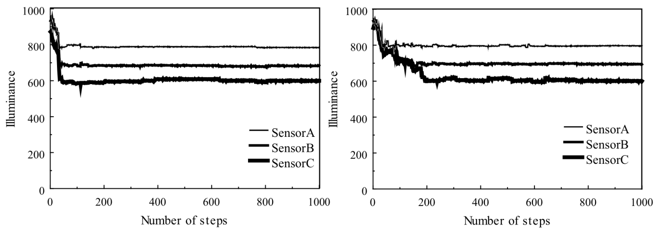
SensorA SensorB

Fig.3 Regression line

4.3 CONVERGENCE

4.3.1 THE ENVIRONMENT IS NOT CHANGEED

The convergence history of illuminance sensors is indicated in Fig.5. Results for ANA/RC are included in Fig.5(a) and the results for ANA/CC are included in Fig.5(b). Fig.5(a) indicates convergence into the target illuminance value after approximately 50 steps (about one minute). This result shows that it takes approximately half time to converge into the target illuminance compared to ANA/CC in Fig.5(b); therefore ANA/RC also presents superior performance from the viewpoint of convergence into the target illuminance.



(a) ANA/RC (b)ANA/CC

Fig.5 Result of Experiment 1

Next, we evaluated that whether or not accurate position relation is obtained when the number of lights increases. The regression coefficient history for sensor A is indicated in Fig.6. The X-axis represents the number of steps and the Y-axis represents regression coefficient. The results for sensor B and C and indicate in Fig.7.

The results of the regression coefficient for the five lights near the illuminance sensor are indicated with a black straight line or wave line, and others are indicated in gray. The history of the light positioned right above the illuminance sensor is indicated with the bold wavy line. Since lights 1,2,4,6 and 7 exist near sensor A, their history is indicated in black.

Based on the results of Fig.6, the regression coefficient for light 4 located the closest is the highest in the case of sensor A, and decreases in the order of lights 4,1,6,2 and 7. The correlation coefficient for the light at a distant position (indicated in light color) gathers around 0; therefore actual

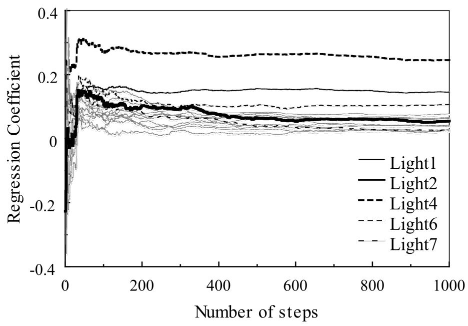
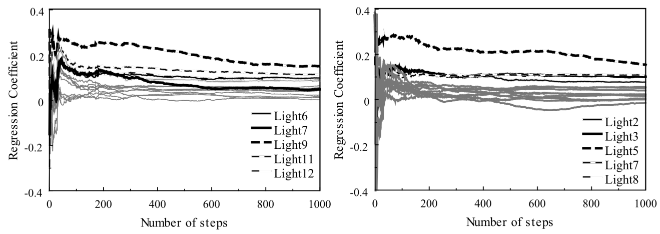


Fig.6 History of regression coefficient for sensor A



(a) sensor B (b) sensor C

Fig.7 History of regression coefficient for sensor B and C

position relation between sensor A and 15 lights are obtained accurately.

The regression coefficient for light 1 and 6 is larger than light 2 and 7, it could be said that it is increased due to reflection from walls. Based on the results of Fig.7, the regression coefficient for lights near the illuminance sensor becomes high, and position relations could be determined steadily.

4.3.2 THE TARGET ILLUMINANCE IS CHANGED

We evaluated the ability to re-converge into the target illuminance when the target illuminance value for illuminance sensor A is changed from 600lx to 750lx at 500 steps. The results for ANA/RC are indicated in Fig.8 and results for ANA/CC are indicated in Fig.9. The target illuminance is changed upon passing 500 steps, but sensors except illuminance sensor A were not affected in the case of ANA/RC, indicating that the target illuminance was successfully changed. This is considered to be because accurate positions were successfully determined with regression analysis, and the target illuminance was achieved only by the change in luminance (increased luminance) of the lights with a high level of impact. On the other hand, the time required for re-convergence after changing the target illuminance is slightly longer in the case of ANA/CC, compared with ANA/RC. With both methods, the change in the target illuminance can be achived within approximately one minute. ANA/RC is considered to be superior because of its high ability of convergence into the target illuminance.

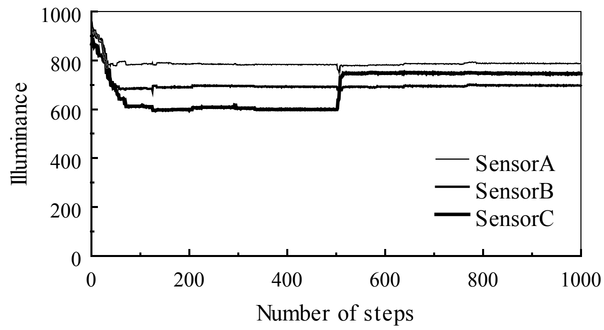


Fig.8 History of illuminance (Exp.2:ANA/RC)

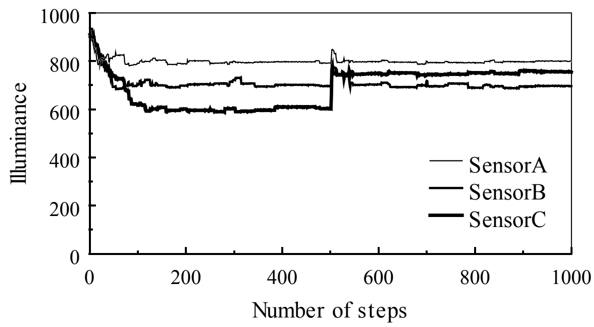


Fig.9 History of illuminance (Exp.2:ANA/CC)

4.3.3 THE ILLUMINANCE SENSOR IS MOVED

We evaluated the ability to re-converge into the target illuminance when the position of illuminance sensor C is changed after each illuminance sensor reaches the static condition. The history of illuminance is indicated in Fig.10 and 11. The X-axis represents the number of steps and the Y-axis represents illuminance values.

In Fig.10 and 11, re-convergence into the target illuminance after the move of the illuminance sensor is achieved at approximately 100 steps in both methods, indicating that they are equivalent in terms of the ability of convergence. However, the difference is that the illuminance value for ANA/RC does not increase immediately after the move of the illuminance sensor, while the illuminance value for ANA/CC increases immediately after the move of all sensors. It is also showed that the change in luminance for ANA/RC is small until the regression coefficient value for Light 10 increased. On the other hand, in ANA/CC, the move of sensor C leads to the increase of luminance values of other lights and the increase of illuminance value of sensors. In ANA/RC, illuminance sensor C is not achieved the target illuminance value until the position relation after the move is determined. ANA/CC could be superior from the viewpoint of achieving the target illuminance; however ANA/RC is superior from the viewpoint of minimizing the affect on other illuminance sensors. From the aspect of energy conservation, it is more effective to use the regression coefficient even though it takes time to achieve the target illuminance.

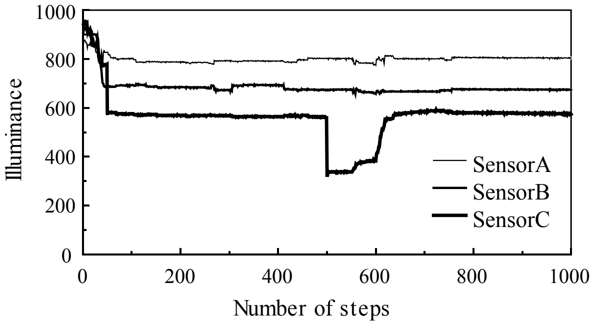


Fig.9 History of illuminance(Exp.3:ANA/RC)

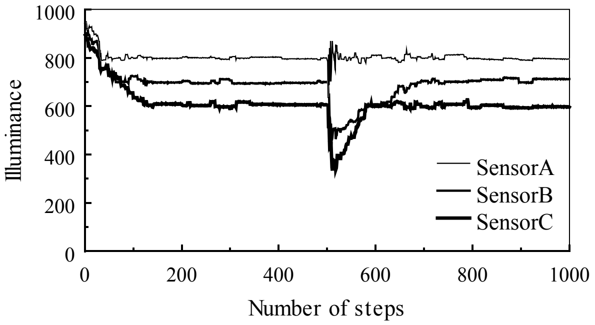


Fig.9 History of illuminance(Exp.3:ANA/CC)

5. SUMMARY

It is possible to determine the position relation between the light and the illuminance sensor based on changes in the luminance and room illuminance. The minimum luminance to a necessary location provides an energy-saving lighting pattern. To identify position relation also seems significant because it could promptly respond to the change in the environment such as the change in the target illuminance.

We has proposed ANA/CC and showed its effectiveness. ANA/CC evaluates the correlation in relation to the change in luminance of lights and the change in illuminance of illuminance sensors, and determines that light and illuminance sensors with high correlation are closely positioned. We experimentally showed that ANA/CC could estimate the relative position relation between light and illuminance sensor by using a correlation coefficient, and indicated high performance compared with a method that does not consider position relations. However, the correlation coefficient is obtained in accordance with the difference in luminance value of the light and illuminance value of the illuminance sensor, therefore, it was found that accurate position might not be determined. If it is possible to determine the position relation in more accurately, effective lighting patterns can be estimated.

Therefore, we proposed the Adaptive Neighborhood Algorithm using Regression Coefficient (ANA/RC) in this paper. With ANA/RC, the position relation between the light and the illuminance sensors is calculated with regression analysis in accordance with the change in luminance and the change in illuminance. It is possible to obtain the position relation with high accuracy when it is difficult to estimate the position relation by using a correlation coefficient in a data.

Using 15 dimmable fluorescent lights and three illuminance sensors, we experimentally showed that the position relation obtained from regression coefficient is confirmed to be equivalent to the position relation between the the illuminance sensor and the light. Convergence performance to the target illuminance is also high, and in regards to the move of illuminance sensors, it is indicated that re-convergence to the target illuminance is possible with minimal impact. Based on the above, these results demonstrate the effectiveness of the proposed method. ANA/RC could improve the accuracy in determining the position relation between the light and the illuminance sensor.

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