Reducing the number of lighting control attempts before Illuminance Convergence in the Intelligent Lighting System using the Layout Map of Lightings and Illuminance Sensors

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Abstract— *We research and develop an Intelligent Lighting System to realize the illuminance levels required by each office worker. This system controls each lighting appropriately for the level influence by the lighting's luminance on illuminance sensor measurements (illuminance/ luminance influence factor). And by using illuminance/ luminance influence factor, the system quickly realized illuminance levels requested by workers even in larger-scale offices. In the past cases, we were allowed to measure illuminance/ luminance influence factors in the actual office before designing an Intelligent Lighting System. However, it is not always easy to have access into a user's office prior to installation to measure illuminance/ luminance influence factors: this inaccessibility has been a challenge to the popularization of Intelligent Lighting Systems. This study proposes a method to reduce the number of illuminance control attempts before illuminance convergence without using illuminance/ luminance influence factors.*

Keywords: Lighting, Intelligent Lighting System, illuminance simulation, illuminance sensor

1. Introduction

In recent years, there has been a rise in attention to approaches for improving the intellectual productivity, creativity and comfort of office workers [1]. A study by Boyce et al. have revealed that providing the brightness (illuminance) optimized for the work of each worker is effective from the viewpoint of improving the lighting environment[2]. Against this backdrop, the authors have undertaken studies on Intelligent Lighting Systems aimed at improving worker comfort in offices and reducing power consumption by lightings[3],[4]. An Intelligent Lighting System realizes the illuminance level requested by each worker (target illuminance) at the relevant illuminance sensor position with a minimum power consumption. An office with an Intelligent Lighting System is expected to allow workers to work in lighting environments customized for each of them, which will improve their comfort and reduce their stress. Moreover, providing the necessary levels of luminance at areas in need can lower the average illuminance in the whole room, which will result in a significant reduction of power consumption. As these advantages of Intelligent Lighting Systems are recognized, verification experiments have been underway at several offices in Tokyo, which have successfully realized required illuminance levels at the points where they are required, realizing high energy efficiency[5].

Intelligent Lighting Systems use a lighting control algorithm called Adaptive Neighborhood Algorithm using Regression Coefficient (ANA/RC) based on a hill climbing method for the optimization of lighting patterns[3],[6]. The ANA/RC varies the luminance of each lighting appropriately by using the level of influence (hereinafter referred to as illuminance/ luminance influence factor) on the measurement of each illuminance sensor. To dynamically learn the illuminance/ luminance influence factor, the ANA/RC performs regression analysis based on luminance variations and illuminance variations occurring upon microscopic variations in the luminance of lighting fixtures. Besides, since each worker is assigned a desk in a fixed position in most offices, illuminance sensor positions are also fixed already: hence, the illuminance/ luminance influence factors for each illuminance sensor can be measured by turning on and off lighting fixtures one by one in the office before introducing an Intelligent Lighting System.

An Intelligent Lighting System realizes the target illuminance for each worker by conducting about 30 to 100 lighting control attempts each spanning about one second. However, there is a concern that in larger-scale offices, the numbers of lighting fixtures and illuminance sensors will be larger, and the time required for each lighting control attempt will be longer. When illuminance/ luminance influence factors are known in accurate terms, then an accurate simulation of the user's office environment will be possible with considerations for effects of factors unique to the environment, such as reflections of lighting fixtures' light by walls or the effects of partitions, which cannot be known from a lighting layout map alone. By quickly deriving lighting patterns which achieve the target illuminance levels requested by workers in a simulated environment, and applying them to the real user environment, the system was able to quickly realize the target illuminance level for each worker[7]. In this way, an Intelligent Lighting System installed in a large scale environment can realize target illuminance levels requested by workers at a speed equivalent to or higher than in past applications.

However, while the system learns illuminance/ luminance influence factors by regression analysis, temporary correlation phenomenon between random numbers may occur, to cause a regression coefficient of a lighting fixture distant from an illuminance sensor to be assessed too highly. For this reason, an accurate estimation of illuminance/ luminance influence factors takes a very long time. Besides, sometimes the user's office may not readily allow the entry of outsiders for illuminance/ luminance influence factor measurement, which can be a factor hindering Intelligent Lighting Systems from being more popular.

This study proposes an alternative approach to reducing the number of lighting control attempts before illuminance level convergence is reached, instead of using illuminance/ luminance influence factors which require estimation or measurement. Verification experiments demonstrate that the number of illuminance/ luminance control attempts before reaching illuminance level convergence can be reduced even without using illuminance/ luminance influence factors which require either estimation or measurement. The study aims to make Intelligent Lighting Systems easier to introduce by eliminating the need of illuminance/ luminance influence factor measurement in the user environment.

2. Intelligent Lighting System

2.1 Construction of Intelligent Lighting System

An Intelligent Lighting System realizes an illuminace 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, illuminance sensors, 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 from illuminance sensors 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 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)[3],[6]. 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

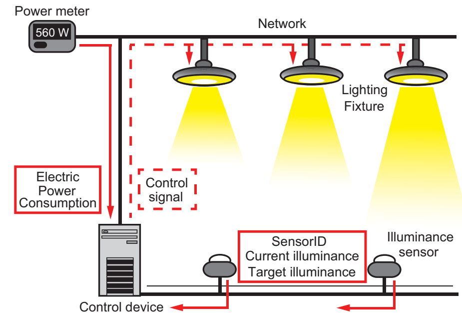

Figure 1: Configuration of the Intelligent Lighting System

varies the luminance of each lighting fixture in each search to an extent unnoticeable by workers to search an optimum lighting pattern. By repeating lighting control attempts of about a second 30 to 100 times, an Intelligent Lighting system realizes the target illuminance level requested by each worker.

The Intelligent Lighting System aims to adjust the illuminance to equal or greather than the target illuminance fot the location where the sensors are installed, and autonomously finds the lighting intensity to minimize the amount of electrical power used for lightings. This illuminance must be formulated as an objective function. The objective function is indicated in the Eq. 1.

$$f_i = P + w \times \sum_{j=1}^{n} R_{ij}(I_j - I_j^*)^2 \tag{1}$$

i : lightng ID, j : illuminance sensor ID
P : power consumption [W], w : weight
n : number of illuminance sensors
R : illuminance/ luminance influence factor [lx/cd]
I : current illuminance [lx], I^* : target illuminance [lx]

As indicate in the Eq. 1, the ovjective function consists of power consumption and illuminance constraint. Also, changing weight w enables changes in the order of priority for electrical energy and illuminance constraint. The illuminance constraint brings current illuminance to target illuminance or greater, as indicated by formula.

2.3 Illuminance/ luminance influence factor

It is known that the luminance of a lighting fixture is in proportion to the illuminance sensor measurement, which is shown by Eq. 2.

$$I = RL \tag{2}$$

I : illuminance [lx], L : luminance [cd]
R : illuminance/ luminance influence factor [lx/cd]

The illuminance/ luminance influence factor R is a value dependent on the working environment, which is considered to be a constant unless there is a change to the lighting environment.

In ANA/RC, the illuminance/ luminance influence factor of a lighting fixture to an illuminance sensor is estimated by regression analysis based on luminance variations and illuminance sensor measurement variations which occur when the lighting fixture luminance is varied in microscopic steps. It takes about 2 minutes for the system to learn an illuminance/ luminance influence factor because it needs to vary the luminance of lightings about 120 times. Besides, since each worker is assigned a desk in a fixed position in most offices, illuminance sensor positions are also fixed: hence, the illuminance/ luminance influence factors for each illuminance sensor can be measured by turning on and off lighting fixtures one by one in the office before introducing an Intelligent Lighting System. In the past applications of Intelligent Lighting Systems in actual offices, we were allowed to enter the user ' s office before installation to measure illuminance / luminance influence factors.

2.4 Reducing the number of lighting control attempts before illuminance convergence

When the scale of the environment of an Intelligent Lighting System is larger, the number of lighting fixtures and illuminance sensors will be larger. This may prolong the time required for the transmission of light control signals to a lighting fixture and the acquisition of illuminance data from an illuminance sensor, prolonging each attempt of lighting control, causing the total time required to realize the target illuminance for each worker to be longer than in the past.

When the illuminance/ luminance influence factor of each lighting fixture to each illuminance sensor is accurately known, the illuminance at the illuminance sensor in any given lighting pattern can be calculated from Eq. 2. Hence, an accurate simulation of the user's environment is possible taking account also of factors unique to the environment which are not known from a lighting layout map alone, such as the reflection of light from lighting fixtures by walls or the effects of partitions. By quickly deriving a lighting pattern which achieves the target illuminance level requested by each worker in a simulated environment and controlling lighting fixtures accordingly, the system was able to realize the target illuminance level for each worker with a single lighting control attempt. Furthermore, also in an environment with daylight, the target illuminance level requested by each worker was achieved within two lighting control attempts, by estimating the illuminance of daylight from the illuminance sensor measurement obtained in the first lighting control attempt, then using the estimated daylight illuminance value in the second control attempt (hereinafter referred to as simulation method) [7]. This demonstrates that using this approach, Intelligent Lighting System applications in large-scale environments can also realize target illuminance levels requested by workers more quickly than in the past.

2.5 Challenges for the estimation/ measurement of illuminance/ luminance influence factors

In estimating illuminance/ luminance influence factors using regression analysis, the change in illuminance at an illuminance sensor may be similar to the change in luminance of a lighting fixture distant from an illuminance sensor by chance, causing the regression coefficient of a lighting fixture distant from an illuminance sensor to be assessed too highly. For this reason, it is not easy to correctly estimate illuminance / luminance influence factors within the learning time of about 2 minutes: it will require quite a long time for the system to learn the illuminance/ luminance influence factors of lighting fixtures on each illuminance sensor with accuracy. For this, to achieve the target illuminance level for each worker quickly, it is desirable that illuminance/ luminance influence factors are known from the beginning.

By measuring in the user ' s environment before installation, accurate measurements of the illuminance/ luminance influence factors can be obtained without resorting to estimation based on regression analysis. However, sometimes the user's office may not readily allow the entry of outsiders for illuminance/ luminance influence factor measurement, which can be a factor hindering Intelligent Lighting Systems from being more popular. In some cases, a tenant objecting to an entry by outsiders may hinder illuminance/ luminance influence factor measurement. In order to make it easier to introduce Intelligent Lighting Systems and increase their popularity, an alternative approach to reduce the number of lighting control attempts before reaching illuminance convergence will be needed which does not rely on illuminance/ luminance influence factors requiring either estimation or measurement.

3. Reducing the number of lighting control attempts without using illuminance/ luminance influence factors

3.1 Fundamental principles of the proposed method

Here we propose an alternative approach to reduce the number of lighting control attempts without using illuminance/ luminance influence factors which require estimation or measurement. In the proposed method, the illuminance value at each illuminance sensor is calculated from the luminance data of lighting fixtures, based on the illuminance sensor positions relative to lighting fixtures known from a lighting fixture/ illuminance sensor layout map. In this way, the user ' s environment can be simulated more easily than by using illuminance/ luminance influence factors. By quickly deriving a lighting pattern which realizes the target illuminance level requested by each worker in a simulated environment and controlling lighting fixtures accordingly,

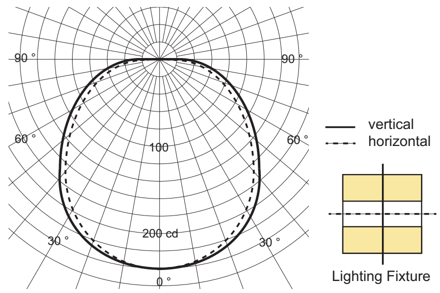

Figure 2: Luminous intensity distribution curve

the system quickly realizes the target illuminance level for each worker with a smaller number of lighting control attempts.

3.2 Formula of illuminance based on the illuminance sensor position

The relation between the luminance of a lighting fixture and illuminance at an illuminance sensor is expressed by Eq. 3.

$$I = \frac{L}{d^2}\cos\theta \tag{3}$$

I:illuminance [lx], L:luminance [cd]
d:Straight line distance from the lighting [m]
θ:vertical angle of the lighting to the sensor

From Eq. 3, the illuminance value at the illuminance sensor is calculated based on the straight line distance and the vertical angle from the lighting fixture. However, because Eq. 3 does not take account of the radiation characteristics of the lighting, the calculated illuminance value will include an error relative to the straight line distance between the lighting fixture and the illuminance sensor. Thus, the radiation characteristics of the lighting need to be considered. The radiation characteristics of the lighting can be known from the luminous intensity distribution curve, which is released as a design data for general lighting products. Fig. 2 shows the luminous intensity distribution curve of the LED lighting system manufactured by SHARP Corporation which is used in our verification experiment to be mentioned later.

From Fig. 2, the larger the vertical angle of the lighting to the illuminance sensor is, the more the luminance toward that direction is attenuated. Thus, errors in illuminance calculation can be lessened by considering the attenuation of luminance relative to the vertical angle based on the luminous intensity distribution curve.

3.3 Control algorithm of proposed method

The number of lighting control attempts before illuminance convergence is reduced by applying the lighting pattern obtained from simulation to each lighting fixture. To calculate the illuminance value at an illuminance sensor, the illuminance from daylight needs to be considered. The illuminance from daylight at the illuminance sensor position is expressed by Eq. 4.

$$D = I_j - I_L \tag{4}$$

j:illuminance senor ID
D:illuminance from daylight [lx]
I_j:illuminance acquired from the illluminance sensor [lx]
I_L:illuminance from lightings [lx]

Now the illuminance from a lighting fixture in a simulated environment is calculated, then the illuminance from daylight is estimated using Eq. 4. The proposed method uses the following control steps:

1) Each worker sets a target illuminance.
2) The system obtains illuminance information from the illuminance sensor.
3) The illuminance from daylight is estimated from Eq. 4.
4) A lighting pattern taking account of daylight in the simulated environment is obtained from calculation.
5) The system applies the lighting pattern obtained from calculation to the lighting fixture.
6) When the worker modifies the target illuminance, return to steps (1).

To respond to the constant variation of illuminance from daylight, steps (2) through (6) are repeated.

Because the proposed method cannot take account of factors unique to the user's environment, there occurs a difference between the illuminance calculated from simulation and the measurement by the illuminance sensor. The estimated illuminance from daylight should be inaccurate for this reason, but in any case, the system realizes the target illuminance requested by the worker by regarding this difference between the illuminance sensor measurement and the illuminance calculated from simulation as the illuminance from daylight.

4. Verification experiment

4.1 Verification experiment overview

To demonstrate the effectiveness of the Intelligent Lighting System using the proposed method, a verification experiment was conducted. An experimental environment as shown in Fig. 3 was configured with nine lighting fixtures and three illuminance sensors (A, B and C). In an experimental room measuring 5.4m x 5.4m x 2.45m, illuminance sensors were installed at the height of 0.7m above the floor, which is the height of an office desk recommended by JIS. As lighting fixtures, dimmable LED lighting system manufactured by SHARP was used.

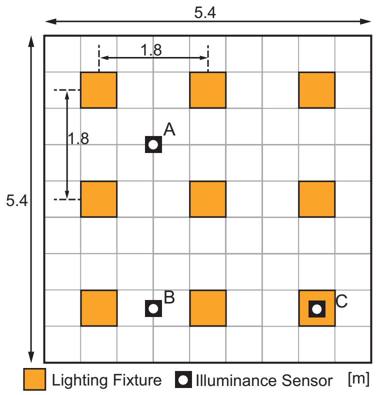

Figure 3: Experiment Environment（ground plan）

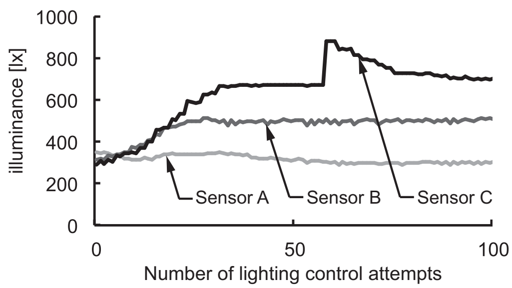

Figure 4: Illuminance History in ANA/RC

4.2 Comparison experiment concerning the number of lighting control attempts and lighting statuses

In the experimental environment shown in Fig. 3, an experiment concerning illuminance convergence was conducted. For illuminance sensors A, B and C, the target illuminance was set to 300 lx, 500 lx and 700 lx respectively. To verify the effectiveness of the proposed approach taking account of daylight, light from a fluorescent lamp was introduced to illuminance sensor C after 60 lighting control attempts. Illuminance convergence was tested for each of the ANA/RC, the simulation method and the proposed method. The intention was to verify the effectiveness of the proposed method by comparing the illuminance histories and lighting statuses between different methods.

The illuminance histories of the three illuminance sensors with ANA/RC are shown in Fig. 4; the illuminance histories of the three sensors with the simulation method in Fg.5; and the illuminance histories of the three sensors with the proposed methods in Fig. 6. Also the statuses of the lighting after 200 lighting control attempts in the three methods are shown in Fig. 7. From Fig. 4 and 6, about 30 lighting control attempts were required to realize the target illuminance level with ANA/RC, while one attempt of lighting control was enough to realize the target illuminance level with the

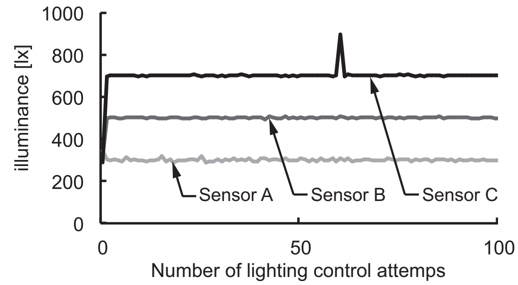

Figure 5: Illuminance History in Simulation Method

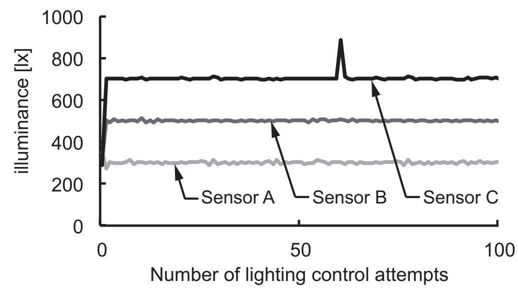

Figure 6: Illuminance History in Proposed Method

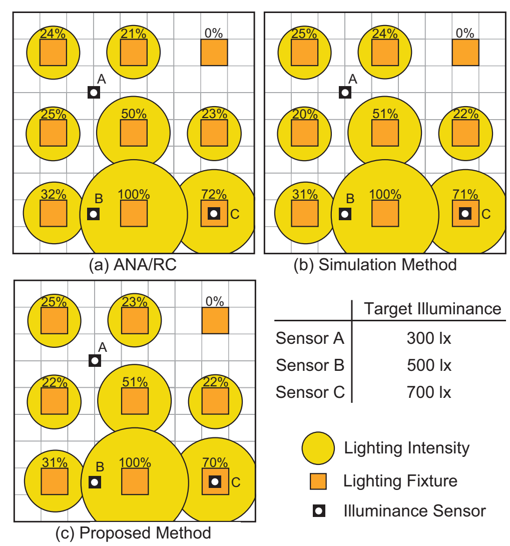

Figure 7: Satus of Lighting（200 lighting control attempts）

proposed method. From Fig. 5 and Fig. 6, no significant difference is found between the illuminance histories from the simulation method and the proposed method. The illuminance histories from the three methods show also that the introduction of the illuminance from daylight temporarily raises the illuminance measurement of illuminance sensor C at the point of 60 lighting control attempts. From Fig. 6, with the proposed method however, one attempt of lighting control was enough after the illuminance from daylight was

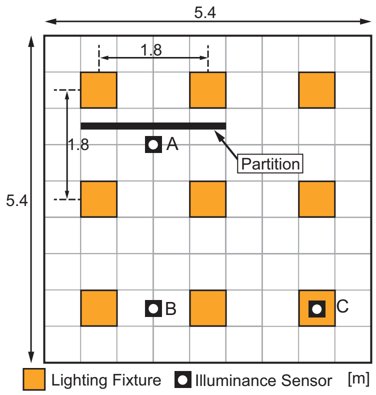

Figure 8: Experiment Environment（ground plan）

detected by the illuminance sensor for the system to realize again the target illuminance level. Next, from Fig. 7, a comparison between the lighting statuses resulting from the three methods shows that the three methods alike realized similar lighting patterns. These results demonstrate that the proposed method can reduce the number of lighting control attempts while quickly realizing the target illuminance level for each worker.

5. Verification experiment in a partitioned environment

5.1 Verification experiment overview

With the proposed method, it is not possible to take into consideration from the beginning the reflections of lighting fixtures's light by walls or shielding by partitions. Out of all, shielding by partitions has particularly large effects on illuminance measurements by illuminance sensors. Hence, an experiment was conducted to verify the effectiveness of an Intelligent Lighting System using the proposed method in a partitioned environment. An experimental environment was configured as shown in Fig. 8 in which a 1.8 m-high partition was installed above illuminance sensor A.

5.2 Comparison experiment concerning the number of lighting control attempts and lighting statuses

An illuminance convergence experiment was conducted in an experimental environment shown in Fig. 8. Under the conditions same as those used in the experiment in Chapter 4, illuminance convergence was tested with ANA/RC, the simulation method and the proposed method. To verify the effectiveness of the proposed method, illuminance histories and the lighting statuses from the three methods were compared.

Fig. 9 shows the history of illuminance at each illuminance sensor in the ANA/RC method; Fig. 10 shows the history of illuminance at each illuminance sensor in the simulation method; and Fig. 11 shows the history of illuminance at each illuminance sensor in the proposed method. Also, the statuses of lighting after 200 lighting control attempts in the three methods are shown in Fig. 12. From Fig. 9, with ANA/RC, about 30 lighting control attempts were required to realize the target illuminance level. In contrast, Fig. 11 shows that in the proposed method, the target illuminance was achieved with only one control attempt for illuminance sensor B and illuminance sensor C, and with two control attempts for illuminance sensor A which is more affected by the shielding effect of the partition. Based on Fig. 10 and Fig. 11, between the proposed method and the simulation method, the difference in the number of lighting control attempts required before illuminance convergence was only one at the greatest, which is not significant. Next, from Fig. 12, with ANA/RC and the simulation method, an energy-

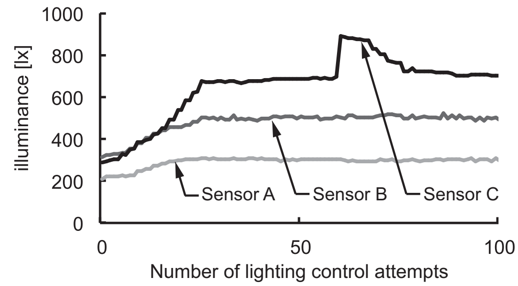

Figure 9: Illuminance History in ANA/RC

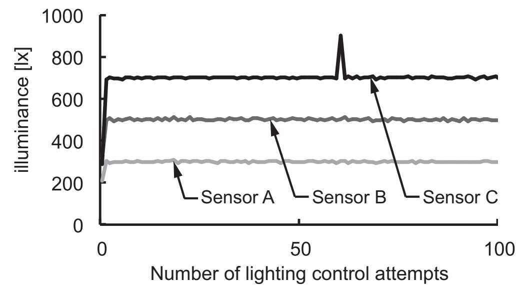

Figure 10: Illuminance History in Simulation Method

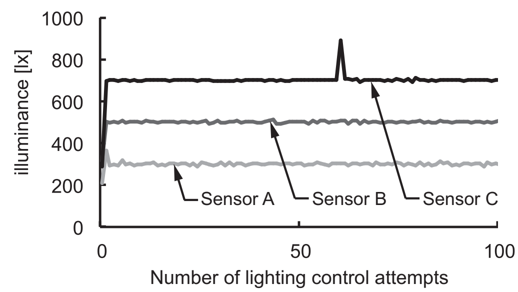

Figure 11: Illuminance History in Proposed Method

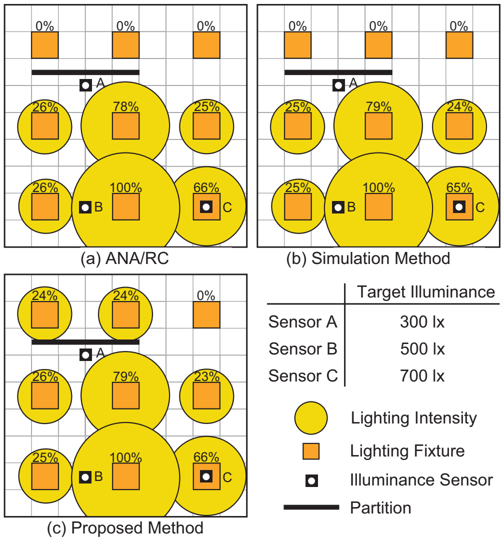

Figure 12: Satus of Lighting (200 lighting control attempts)

efficient lighting pattern is realized with the lighting fixtures above the partition turned off, as they have no effect on the illuminance sensor. In contrast, the proposed method fails to realize an optimum lighting pattern, without turning off the lighting fixtures above the partition.

These results demonstrate that the proposed method can quickly realize the target illuminance level desired by each worker even in a partitioned environment with a small number of lighting control attempts. However, because the proposed method incorporates no means to detect the presence of a partition, it turns on also those lighting fixtures which have no effect on illuminance sensors. Hence, the results indicate also that the lighting pattern may be less energy efficient with the proposed method than with ANA/RC or the simulation method.

owever, most partitions used in Japanese offices are short types which are not likely to block the effect of lighting influential on an illuminance sensor. Therefore, we consider that in reality, there will not be many cases where the proposed method sacrifices energy efficiency in determining its lighting patterns compared to the conventional method. Furthermore, in cases where a tall partition is to be installed, we also consider using a layout map including partitions to configure a simulated environment taking account also of any light-shielding structures.

Fig. 13 shows the side view of a partitioned environment in which an Intelligent Lighting System is installed. In such a case, the value of luminance from the lighting fixture is reduced in relation to the share of the shield to the arrowed range when configuring a simulated environment. It is considered that by incorporating the shielding effect of partitions from the beginning in this way, we will be able to realize more energy efficient lighting patterns.

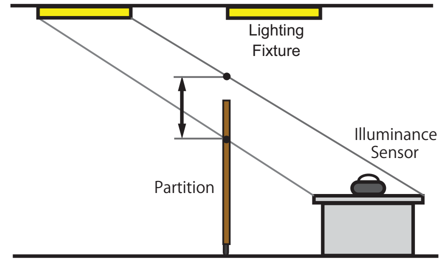

Figure 13: Intelligent Lighting System in a partitioned environment (side view)

6. Conclusion

In this study, we have proposed a method to reduce the number of lighting control attempts before reaching illuminance level convergence without using illuminance/ luminance influence factors. In the proposed method, the positions of illuminance sensors relative to lighting fixtures are checked from a layout map of lighting fixtures and illuminance sensors, then illuminance values are calculated based on the sensor positions. By calculating a lighting pattern which realizes the target illuminance level desired by each worker and applying the pattern to relevant lighting fixtures, the number of lighting control attempts before reaching illuminance convergence can be dramatically reduced. Verification experiments have demonstrated that the proposed method can quickly realize the target illuminance levels desired by each worker while reducing the number of lighting control attempts. Eliminating the need of entering the user's office to measure illuminance/ luminance influence factors before each installation, the proposed method can make Intelligent Lighting Systems easier to introduce.

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