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An Intelligent Lighting System Saving Power Consumption by Estimating Illuminance Sensor Positions

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Abstract: We are doing researching and development of an intelligent lighting system to provide desired brightness to a desire place. To realize individual lighting environments, this system needs the influence level of each lighting and each illuminance sensor. Also, by measuring the influence level that dynamically, this system can cope with dynamic illuminance sensor relocations (user relocations). If this system don't consider illuminance sensor relocations, this system can turn off lightings of little influence. Therefore, this system leads to energy saving. However, it is impossible to be successful at both illuminance sensor relocations and turning off lightings (improvement of energy efficiency). To solve this problem, this paper proposes a new lighting control algorithm which estimates illuminance sensor positions based on distances from turned-on lightings. It will enable the lighting system to learn the change in user or desk positions, and turn off those lightings which affect users very slightly. we conducted an experiment to simulate a real office. As a result, we indicate that the algorithm can realize the illuminance level desired by users while further saving energy consumption.

1. Introduction

It has been reported that, to realize a better office environment, providing an illuminance optimized for each worker's task is effective for raising worker productivity[2]. One lighting solution which can realize individualized illuminance levels in an office environment is a task-ambient lighting system[3]; but in Japanese offices, task-ambient lightings are rarely adopted. This is because typical office buildings are equipped with ceiling lighting fixtures which provide a uniform illuminance, and most companies are unwilling to pay extra costs for adding task-ambient lightings. Considering these, there is a need of a lighting control system which provides light optimized for each office worker using only ceiling lighting fixtures.

Against this backdrop, the authors have proposed an intelligent lighting system which can provide brightness as required by users at any given points specified by users, depending only on ceiling lighting fixtures[4], [5]. The intelligent lighting system is composed of lighting fixtures, a lighting control devices, illuminance sensors (one person holds one illuminance sensor), and an electrical power meter. With this intelligent lighting system, each user specifies a target illuminance level for an individualized illuminance sensor placed on the desktop, then the system will follow a lighting pattern which realizes the target illuminance level while minimizing energy consumption using an optimization method. One should also note that this intelligent lighting system does not consider turning off part of lightings in the office to cope with dynamic changes in environmental conditions such as user relocations and change in desk positions.

The intelligent lighting system has proven successful in our laboratory experiments[6]. Toward the commercialization of our intelligent lighting systems, currently verification experiments are underway in several offices in Tokyo and Fukuoka[7]. In the experiment, it was found that users hardly changed desk positions in these offices. Under such circumstances, we introduced a lighting control algorithm which turns off lights in places requiring no brightness to further improve the energy efficiency.

On the other hand, there are many "non-territorial" offices where users can move or change desk positions rather frequently. In view of this, this paper proposes a new lighting control algorithm which estimates illuminance sensor positions even after they are relocated. It will enable the system to cope with user relocations and desk position changes, while turning off those lightings which hardly affect users.

In this study, an operational experiment simulating a real office environment was conducted to verify the effectiveness of the proposed system.

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

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changing the luminous intensity of lightings. The intelligent lighting system, as indicated in Fig.1, is composed of lights equipped with microprocessors, portable illuminance sensors, and electrical power meter, with each element connected via a network.

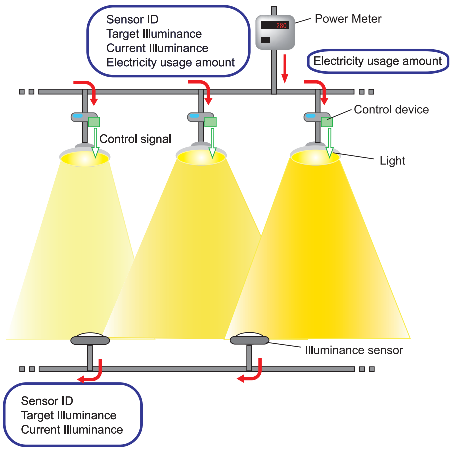


Fig. 1 Configuration of intelligent lighting system

2.2 Adaptive Neighborhood Algorithm using Regression Coefficient(ANA/RC)

The control algorithm is a critical element for the control of an intelligent lighting system. The speed of convergence to the target illuminance as well as its accuracy depends largely on the lighting control algorithm. As the best algorithm presently available for lighting control, we have proposed an Adaptive Neighborhood Algorithm using Regression Coefficient (ANA/RC)[8], which was developed by adapting the Stochastic Hill Climbing method (SHC) specifically for lighting control purposes.

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

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

(1) Each lighting lights up by initial luminance.
(2) Each illuminance sensor transmits illuminance information (current illuminance, target illuminance) to the network. The electrical power meter transmits power consumption information to the network.
(3) Each lighting acquires the information from step 2), and conducts evaluation of objective function for current luminance.
(4) Neighborhood is determined, which is the range of change in luminance based on factor of influence and illuminance information.
(5) The next luminance within the neighborhood is randomly generated, and the lighting lights up by that luminance.
(6) Each illuminance sensor transmits illuminance information to the network. The electrical power meter transmits power consumption information to the network.
(7) Each light acquires the information from step 6), and conducts evaluation of objective function for next luminance.
(8) The system performs regression analysis based on the luminous intensity data from each light and illuminance data from each illuminance sensor to determine the regression coefficient (influence level).
(9) If the objective function value is improved, the next luminance is accepted. If this is not the case, the lighting returns to the original luminance.
(10) If any of the lightings has been at the minimum lighting luminous intensity for a certain time with only a small influence level, the system turns it off (applicable only when there is no illuminance sensor relocation) .
(11) Steps 2) through 10) constitutes one luminous intensity value search operation, which is repeated.

A search operation process (requiring about 2 seconds) consists of steps 2) through 10) above: by iterating this process, the system continues to learn how the lighting affects the illuminance sensor measurement until it realizes the target illuminance with minimum power consumption. Furthermore, by using the influence level found in step 8) as a basis for the evaluation and generation of the next illuminance value, the system can quickly optimize illuminance.

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

$$f = P + w \sum_{i=1}^{n} g_i \tag{1}$$

$$g_i = \begin{cases} (It_i - Ic_i)^2 & I_* \leq |It_i - Ic_i| \\ 0 & otherwise \end{cases} \tag{2}$$

P: Power consumption, w: Weight
Ic: Current illuminance, It: Target illuminance
n: Number of users
I^*: Threshold on illuminance difference

The objective function was derived from amount of electric power P and illuminance constraint g_j. Also, changing weighting factor w enables changes in the order of priority for electrical energy and illuminance constraint. The illuminance constraint is decided so that a difference between current illuminance and target illuminance within a threshold, as indicated by Eq. (2). The threshold value is set as a 50 lx.

3. VERIFICATION EXPERIMENTS IN REAL OFFICE ENVIRONMENTS

From around 2009 onward, we have conducted experiments to verify the effectiveness of the intelligent lighting system in several offices in Tokyo and Fukuoka.

In an intelligent lighting system, to cope with user relocations and change in desk positions, even those lightings which hardly affect users need to be kept on at a minimum luminous intensity level. However, in the offices where our experiments were conducted, workers' desk positions were basically fixed and user relocations were rare. Hence, to further improve the system's energy efficiency, we have introduced a control mechanism which turns off lightings at points requiring no light <item (10) listed in 2.1> in these offices.

In this system, for each illuminance sensor, the IDs of several lightings around it are registered on a database, which are chosen based on the levels of influence of lightings to the sensor. By using the data, each lighting can be controlled optimally and turned off when appropriate. However, this method cannot cope with illuminance sensor relocations.

Meanwhile, not a few offices now use a non-territorial office design, in which workers have no fixed personal desks. In non-territorial offices, users may choose any desk position and user relocations are easy. If the control method which may turn off some lights is introduced in this type of office with a dramatically changing environment <item (10) listed in 2.1>, then the system will not be able to optimize lightings once a user relocation occurs, because it will be impossible to calculate the level of influence by a turned-off lighting onto the relevant illuminance sensor.

One solution to this problem may be to require users to notify the system of every user relocation: then the system turns on all lightings that have been turned off and calculate the influence levels of each lighting to relevant illuminance sensors and update the database. But in a real office, turning on all lights that have been off every time a worker relocates may disturb other workers in the office. In addition, users take time to notify the system that they relocate.

Hence, we propose a new lighting control algorithm for the system to automatically detect a user relocation and turn on only those lights which have a high level of influence over the relocated user.

4. LIGHTING CONTROL ALGORITHM BASED ON ESTIMATED ILLUMINANCE SENSOR POSITIONS

4.1 Basic Idea of the Proposed Method

This study proposes a new lighting control algorithm which can cope with illuminance sensor relocations when some lightings have been turned off. In the study, regression analysis is performed based on the luminous intensity data from lightings which are on and the illuminance sensor data after the relocation, then the new sensor position is estimated based on their influence levels. After that, the lighting closest to the estimated sensor position is identified. If that lighting is off, the system can calculate the influence level by turning it on. This will enable the system to cope with user relocations while minimizing discomforts on other office workers. Moreover, the relocated user does not need to take the trouble of notifying the system of the relocation.

To realize this, the following control steps are added to the intelligent lighting system control algorithm:

(1) The system detects an illuminance sensor relocation.
(2) Regression coefficients for turned-on lightings and the relocated illuminance sensor are calculated.
(3) Based on the regression coefficients obtained from step 2), the distances from turned-on lightings to the relocated sensor are calculated.
(4) Based on the calculated distances, the position coordinates of the relocated illuminance sensor are estimated.
(5) Based on the position coordinates of lightings and the estimated position coordinates of the relocated illuminance sensor, the system finds the lighting closest to the sensor and turns it on if it is off.

Illuminance sensor relocations are detected based on the amount of changes in the illuminance level. When a change in illuminance occurs which cannot be explained from changes in the luminous intensities of adjacent lightings alone, the system assumes it to be a sensor relocation. Unlike our former intelligent lighting systems, position coordinates of each lighting need to be known because relocated sensor positions are estimated from its distances to lightings. Also, for each illuminance sensor, at least three of those lightings which have high level of influence onto the sensor should be on at any point of time. This is to enable the system to estimate the position of a relocated sensor based on the distances from those lightings which are on. Once the position coordinates of the relocated illuminance sensor are estimated, the number of lightings to be turned on is determined more than three.

Using the method described above, the system can turn off those lightings which hardly affect users while coping with user relocations and desk position changes.

4.2 Estimating Distances Based on Regression Coefficients

To estimate distances from turned-on lightings to a relocated illuminance sensor, regression analysis is used. Regression analysis is a method to derive a regression equation to explain the causality relation between change in the explanatory variable L and change in the observed value I, which is shown in this case by Eq. (3):

$$I = \sum_{i=1}^{n} r_i \times L_i + \beta \tag{3}$$

I: Illuminance, r: Regression coefficient
L: Luminous intensity, β: Constant
n: Number of lightings

In an intelligent lighting system, regression analysis is performed using explanatory variable L which is the luminous intensity of a lighting, and an observed value I which is the illuminance measured by an illuminance sensor, to calculate the regression coefficient r. The regression coefficient r, which explains the regression equation, is the level of influence by the lighting to the illuminance sensor. Based on this regression coefficient r, the distance between the lighting and the illuminance sensor is estimated.

The relation between luminous intensity L and illuminance I is expressed by Eq. (4) [9], where illuminance I is in inverse relation with the square of the distance d from the light source. Also, the relation between the distance d from the light source and the regression coefficient r expressed by Eq. (3) is expressed by Eq. (5).

$$I = \frac{L}{p^2} \quad (4)$$

$$\Leftrightarrow d^2 = \frac{L}{I} = \frac{1}{r}$$

$$\Leftrightarrow d = \frac{1}{\sqrt{r}} \quad (5)$$

r: Regression coefficient, I: Illuminance
L: Luminous intensity
d: Distance from the light source

Eq. (5) shown above indicates that the regression coefficient r in the intelligent lighting system indicates an estimation of distance d from the light source (distance between the lighting and the illuminance sensor).

Thus, an experiment was conducted to verify the distances between lightings and illuminance sensors and their relation with regression coefficients. In the experiment, 15 neutral white fluorescent lamps (Panasonic FHP45EN) and 4 illuminance sensors were installed as shown by Fig.2, and between each lighting and each illuminance sensor, the distance and the regression coefficient were calculated.

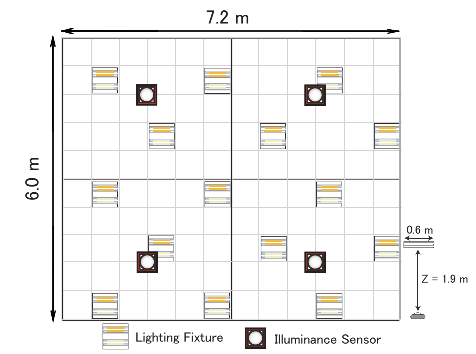


Fig. 2 Experimental environment to obtain regression coefficients

Fig.3 shows the distances between lightings and illuminance sensors and respective regression coefficients.

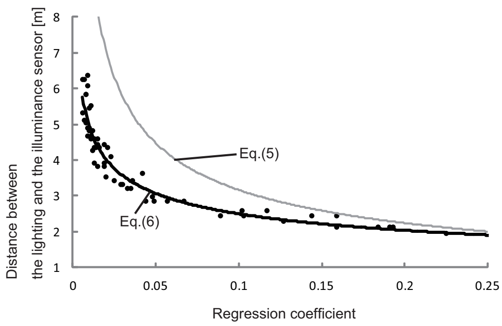


Fig. 3 Relation between the regression coefficient and distance

Fig.3 compares the regression coefficients obtained from the experiment were with the Eq. (5). The result indicates that when the distance between the lighting and illuminance sensor is shorter, the disparity is smaller; when the distance is larger, the disparity is greater. This is because Eq. (4) does not take account of the lighting fixture's radiation characteristics. Fig.4 shows the luminous intensity distribution curve curve for the fluorescent lamp (Panasonic FHP45EN) used in the experiment.

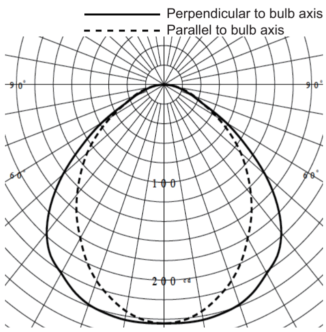


Fig. 4 Luminous intensity distribution curve(FHP45EN)

From Fig.4, one can see that the illuminance on the illuminated plane decrements more when the angle between the lighting fixture and the illuminated plane is larger. In the experimental results shown by Fig.3, the angle is larger when the distance between the lighting and the sensor is larger. Hence, the greater the distance is, the more largely the resulting regression coefficient falls below Eq. (5). Therefore, it is necessary to derive a model taking into account the lighting fixture's radiation characteristics.

In the proposed method, a mathematical model was derived, which estimates the distance based on the regression coefficient obtained through the experiment as shown by Fig.3 using the least square method. The derived mathematical model is shown by Eq. (6).

$$d = 1.8044 \times r^{-3.221} \quad (6)$$

r: Regression coefficient
d: Distance between the lighting and the illuminance sensor

Under this environment, the radiation characteristics of the lighting fixture is taken into account by using Eq. (6), to reduce the error in estimating the distance using the regression coefficient.

4.3 Estimating an Illuminance Sensor Position

Based on the method described in the section above, we can estimate the distance between a turned-on lighting and a relocated illuminance sensor. Based on the estimated distance, the position of the relocated illuminance sensor is estimated using Eq. (7) below.

$$d_i = \sqrt{(X - x_i)^2 + (Y - y_i)^2 + (Z - z_i)^2} \quad (7)$$

d_i: Distance between the turned-on lighting and the illuminance sensor
X, Y, Z: Position coordinates of the relocated illuminance sensor
x_i, y_i, z_i: Position coordinates of the turned-on lighting
i: Number of turned-on lightings

Now because the unknown values are the position coordinates (X, Y, Z) of the relocated illuminance sensor, a unique solution will be found by writing three or more equations. However, for a lighting that is turned off, it is impossible to estimate the distance because there is no way to calculate a regression coefficient concerning any illuminance sensor. Considering this, the system is designed to keep at least three lightings of relatively high influence levels always turned on per illuminance sensor to enable the estimation of position coordinates of relocated illuminance sensors.

Using the method described above, the position of a relocated illuminance sensor is estimated and three or more lights in its vicinity are turned on. This enables the system to calculate the regression coefficient for a lighting near the relocated illuminance sensor which had been turned off.

5. Operational experiment

5.1 Overview of the Operational Experiment

To verify the effectiveness of the proposed method, an operational experiment was conducted for 30 minutes changing luminous intensity of the lighting in 2-second steps (900 steps). For the experiment, 15 lighting fixtures were installed as shown by Fig.5 to simulate a workplace with 3 users (using 3 illuminance sensors). For illuminance sensors A, B and C, the desired illuminance level was set at 300, 400 and 500 lx respectively. The lighting fixtures used were neutral white fluorescent lamps (Panasonic FHP45EN) which had a variable lighting luminous intensity range between a minimum of 30 % and a maximum of 100 %.

In the experiment, when the illuminance value is within the range between +6 % and -8 % of the desired level, the desired illuminance level is deemed to be achieved.

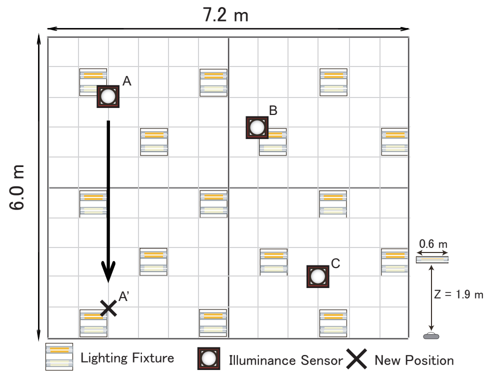


Fig. 5 Experimental environment

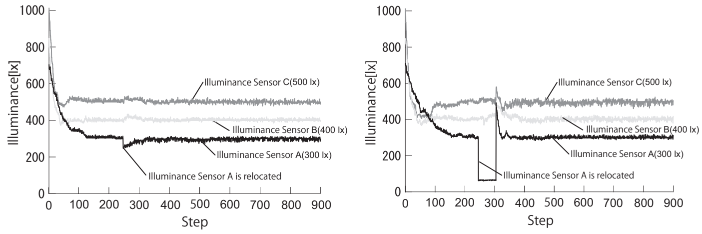
The operational experiment was conducted using the following two patterns to compare the system's performance with a conventional intelligent lighting system as well as to verify the energy saving effect of the new method.

- An operational experiment using our conventional lighting control algorithm (conventional method)
- An operational experiment using a control algorithm incorporating the proposed method (proposed method)

In the operational experiment, after 250 steps, the illuminance sensor A (at illuminance setting point A) is relocated to the new position shown by Fig.5. When an illuminance sensor relocation is detected using the proposed method, the relocated sensor position is estimated using illuminance and luminous intensity data over 60 steps.

5.2 EXPERIMENT RESULTS AND DISCUSSIONS

We checked whether the system realized the desired illuminance level at each illuminance setting point in each of the conventional method and the proposed method. Fig.6 shows the historical illuminance levels from the conventional method and the proposed method.

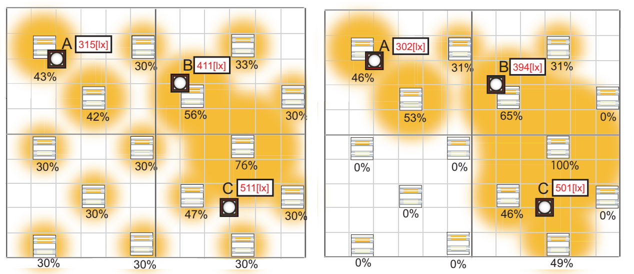


(a)Conventional method (b)Proposed method

Fig. 6 History of the illuminance data

Fig.6 show that in both methods the system realized desired illuminance level at each illuminance setting point. It is shown also that both methods successfully coped with the relocation of illuminance sensor A.

Next, to verify the energy saving effect, the status of each lightings before the sensor relocation at the point of 200th step is shown in Fig.7.



(a)Conventional method (b)Proposed method

Fig. 7 Status of lightings (at the point of 200th step)

From Fig.7-(a) showing the status of lightings in the conventional method, we can see that lightings near each illuminance setting point are turned on at a high luminous intensity level while those distant from an illuminance setting point are turned on at a low luminous intensity level. To cope with sensor relocations, however, all lightings need to be kept on at least at a low luminous intensity level. Meanwhile, from Fig.7-(b) showing the status of lightings in the proposed method, we can see that the lightings near each illuminance setting point are turned on at a high luminous intensity level while those distant from an illuminance setting point are turned off.

Then illuminance sensor A is relocated at the point of 250th step. In the proposed method, after detecting the relocation, the system calculates influence levels concerning turned-on lightings to estimate the new position. Fig.8 shows the estimated and actual

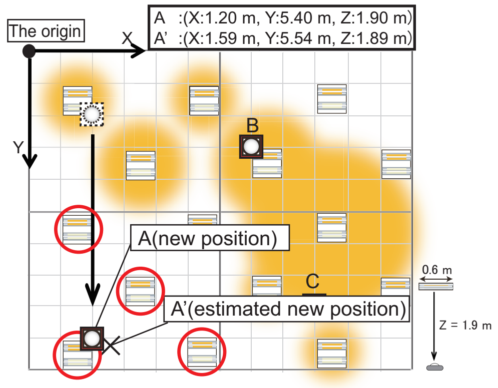
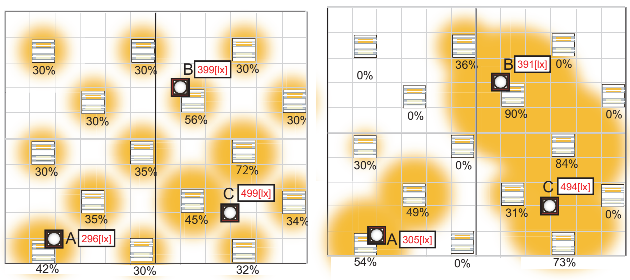


Fig. 8 Status of lightings at the point of 310th step (proposed method)

position coordinates of relocated illuminance sensor A.

Fig.8 shows that the proposed method is able to estimate the position of illuminance sensor A after relocation. This means that by turning on the four lightings (lightings in circles shown in Fig.8 closest to the estimated sensor position, the regression coefficients for the lightings presumed to be most influential can be calculated. Finally, Fig.9 shows the status of lightings after sensor relocation (at the point of 500th step).



(a)Conventional method (b)Proposed method

Fig. 9 Status of each lightings (at the point of 500th step)

Fig.9-(a) shows that in the conventional method, the energy consumption levels of some lightings were lowered after detecting a sensor relocation. But anyway, even lightings of little influence were not turned off but kept on. On the other hand, in the proposed method shown by Fig.9-(b), those lightings expected to have a high influence level are turned on and regression coefficients are calculated. Then based on the calculated regression coefficients, lightings of little influence are turned off to realize a greater energy saving effect than in the conventional method.

From the results of the experiment, it has been demonstrated that the proposed method can also realize the illuminance levels as desired by users while saving energy consumption.

5.3 Comparison of Power Consumption Results

This section compares the power consumption by the lightings between the conventional method and the proposed method. Fig.10 shows the historical records of power consumption by the lightings controlled by the conventional method and the proposed method.

From Fig.10, we can see that the proposed method consumes about 30 % less power than the conventional method. As a result, it has been demonstrated that the proposed method realizes a

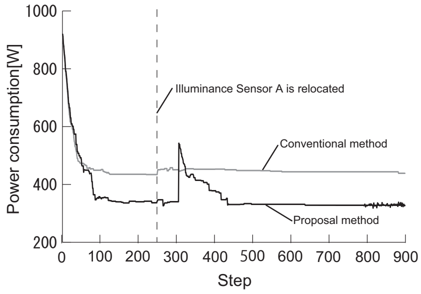


Fig. 10 Historical power consumption by two methods

performance equivalent to the conventional method while further reducing energy consumption.

6. CONCLUSION

Ever since 2009, we have been conducting verification experiments for our intelligent lighting systems at several offices in Fukuoka and Tokyo. Since most of these offices employ a fixed desk system, we introduced an algorithm which turns off lightings of smaller influence levels assuming no user relocations. However, in offices where users often move, once some lightings are turned off, it becomes impossible to measure the levels of influence of those lightings on illuminance sensors.

To solve this problem, we have proposed in this study a new lighting control algorithm which can cope with illuminance sensor relocations by estimating sensor positions using data from turned-on lightings. To verify the effectiveness of the proposed method, an operational experiment was conducted using 15 lighting fixtures and assuming 3 users simulating a real office environment. The experiment demonstrated that the proposed system realizes a performance equivalent to the conventional intelligent lighting system while reducing power consumption.

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