Distributed Optimal Control of the Intelligent Lighting System using Kalman Filter

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ABSTRACT

We are doing research and development of an intelligent lighting system. In the intelligent lighting system, the algorithm which controls lighting fixtures is important. In this research, we examine how to grasp the position relation between the lighting and the illuminance sensors with sufficient accuracy, and we propose a lighting control algorithm which estimates accurate position relation by using the Kalman filter.

1. Introduction

The purpose of lighting in an office is to provide workers with appropriate illumination. At present, as a standard of this brightness, 750 lux is recommended for illuminating a desktop[1]. However, this standard is one that had been set before computers were fully introduced into offices. At present, many people are working on computer displays in most companies. In such cases, it will be possible to reduce the illumination on a desktop lower than this standard. From this viewpoint, we are developing an intelligent lighting system that is possible to provide individuals in offices with different illumination.

In the intelligent lighting system[2], a distributed optimization algorithm is utilized in order to provide different illumination to individual places as well as to minimize power consumption. So far, in this algorithm, the distance between a lighting fixture and an illuminance sensor has been estimated using a correlation coefficient between luminance and illuminance.

In this research, we will formulate the degree of effect of luminance on illuminance that is measured by illuminance sensors using the amount of changes in luminance and illuminance, and will estimate unknown parameters in relational expressions using the Kalman filter[4]. Then, using the results of the degree of effect, we will propose a method for increasing the convergence speed of calculation and the stability of actual illuminance realized.

2. Intelligent lighting system

An intelligent lighting system is a system that connects multiple lighting fixtures to a network to meet user’s requirements by collaborative action between respective lighting fixtures.

2.1 Intelligent lighting system based on a distributed - centralized control scheme

In this research, we divide multiple lighting fixtures in several groups and control illuminance by using control devices that are equipped with each group. Fig.1 shows a schematic diagram of such a system.

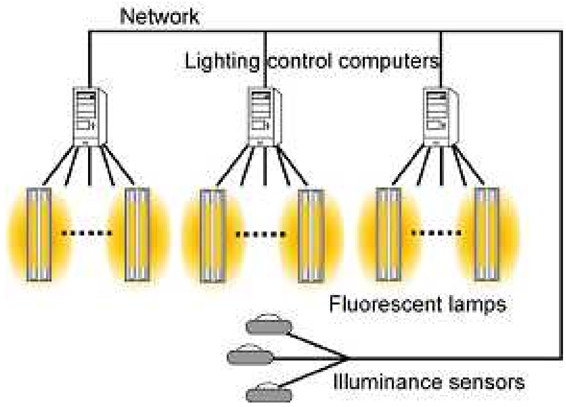

Fig.1 Configuration of the intelligent lighting system based on a distributed - centralized control scheme

2.2 Control algorithm for an intelligent lighting system

In an illuminance control algorithm, in order to obtain target illuminance and to make a shift to a good power-saving state within a short time, it is effective to know the degree of effect of luminance on illuminance. In the Adaptive Neighborhood Algorithm using the Correlation Coefficient (ANA/CC)[3] that is a previous intelligent lighting control algorithm, the correlation between luminance and illuminance has been utilized as a method for autonomously learning the degree of the effect of illuminance.

ANA/CC is a control algorithm that incorporated a neighborhood design utilizing a correlation coefficient for controlling the brightness based on the Stochastic Hill Climbing (SHC) method. In the following, we will describe about the flow of this algorithm.

1. First, we turn on each lighting fixture at an initial luminance and set up a target illuminance on each illuminance sensor.
2. Each lighting fixture obtains the illuminance of each illuminance sensor and its consumed electric power, and calculates the value of an objective function.
3. Each lighting fixture determines an appropriate neighborhood based on illuminance information and the correlation coefficient. In addition, neighborhood means a range to generate the next luminance level.
4. Then, we generate the next level of luminance randomly within the determined neighborhood, and turn on the lighting fixture at that luminance level.
5. We measure illuminance using an illuminance sensor, and calculate the correlation coefficient using luminance and illuminance information obtained from each lighting fixture.
6. Then, we calculate the value of the objective function of the next status. If the value of the objective function was improved, we set the luminance and go on to step-3. On the other hand, if it was not improved, we cancel the amount of luminance change in the calculation and return to step-2.

By repeating the above steps, we will be able to meet the objective illuminance level and make the lighting fixture convergent to a power-saving state[3].

2.3 Objective function

The purpose of the intelligent lighting system is to meet the objective illuminance of each illuminance sensor as well as to realize a power-saving state. Thus, in ANA/CC, as shown by Equation-(1), the objective function is comprised of the first term consisting of the difference between the objective illuminance of the illuminance sensor and the current illuminance, and the second term expressing the amount of power consumption. The consumed electric power is the sum of the luminance of lighting fixtures as shown by Equation-(2). Each lighting fixture is controlled so as to minimize the value of *f*.

$$f = w\sum_{j=1}^{n} g_j + P \qquad (1)$$

$$P = \sum_{i=1}^{m} Cd_i \qquad (2)$$

$$g_j = \begin{cases} 0 & (Lc_j - Lt_j) \geq 0 \\ R_j\left(Lc_j - Lt_j\right)^2 & (Lc_j - Lt_j) \end{cases}$$

$$R_j = \begin{cases} r_j & r_j \geq Threshold \\ 0 & r_j < Threshold \end{cases}$$

n : number of illuminance sensors
m : number of lighting fixtures
w : weight, r : coefficient correlation
P : electricity usage amount
Lc : current illuminance
Lt : target illuminance, Cd : luminance

3. Control algorithm for intelligent lighting system

3.1 Formulating the relationship between amount of luminance change and amount of illuminance change

The change of illuminance in a illuminance sensor can be formulated as Equation-(3) because it is affected by change of luminance of all the lighting fixtures.

$$y_i = \sum_{j=1}^{j} \beta_{ij} x_j \qquad (3)$$

Where, *x* is the amount of luminance change of a lighting fixture, *y* is the amount of illuminance change in an illuminance sensor. B_{ij} is the degree of effect of luminance of lighting fixture *j* on illuminance sensor *i*. As described in section 2.2, the change of luminance in each lighting fixture is random. Therefore, when we consider only the specific lighting fixture, Equation-(3) can be approximated by a regression line expressed by Equation-(4). Because luminance changes in other lighting fixtures are random, they can be estimated as fixed terms since they cancel each other out.

$$y_i = \beta_{0i} + \beta_{1i} x \qquad (4)$$

β_1 is a gradient of the regression line (degree of effect), and β_0 is a y-axis intercept of the regression line. As shown by Equation-(4), it is an observation error of β_0 caused by a luminance change of β_1 (degree of effect) and the observational error of $\beta_{0,}$ caused by the change of luminance of other lighting fixtures. Equation-(4) can be applied to all the lighting fixtures. In this research, we obtain the degree of the effect of luminance on illuminance by obtaining these unknown parameters using the Kalman filter. And, we try to improve convergence by applying the obtained degree of effect to neighborhood selection in generating the next luminance.

3.2 Parameter estimation by using the Kalman filter

The Kalman filter is a theory of filtering to estimate system status and is a Bayesian method that executes estimation using a priori information. In the Kalman filter, the current status is predicted by using an estimated value at one time previous and an observed value, then, a current estimated value is obtained by using this predicted value. Therefore, even if there is a significant error in the observed value, it is possible to obtain a good result for the estimated value

In Equation-(4), error in the observed illuminance value is resulted from noise generated by the luminance change in other lighting fixtures. Since the luminance change in each lighting fixture is decided randomly, we cannot obtain noise information as a priori information. So, we try to minimize this noise by using the degree of effect of each lighting fixture obtained from this estimation as a priori information. That is, we predict the noise by using an estimated value of the degree of effect of other lighting fixtures and the value of luminance change in other lighting fixtures, and eliminate the noise from an observed value actually measured.

3.3 Proposed algorithm

A new control algorithm that we propose in this paper is based on the ANA/CC method. Therefore, the control flow is almost the same as the one in the ANA/CC method described in section 2.2 except for step-3 and step-5. In step-3, we utilize the estimated parameter (degree of effect) instead of the correlation coefficient to determine the appropriate neighborhood. In step-5, we estimate unknown parameters using the Kalman filter from the amount of luminance change and the amount of illuminance change.The objective function used in this proposed algorithm is almost the same as in Equation-(1) except for that R_{ij} uses an estimated parameter (degree of effect) instead of a correlation coefficient.

3.4 Type of neighborhood and its selection method

Fig.2 shows seven types of neighborhoods that are used for generating the next luminance of lighting fixtures in the proposed algorithm.

The degree of effect of each lighting fixture is ranked categorized into four stages; high, medium, low and none using the degree of effect on each illuminance sensor and threshold values T_{high}, T_{middle} and T_{low}. These threshold values are determined experimentally. Depending on the ranking and illuminance value of the illuminance sensor, the neighborhoods shown in Fig.2 are adaptively used. A selection method is described below.

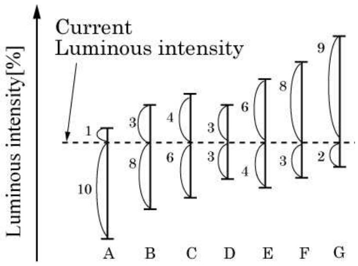

Fig2. Seven types of the neighborhood

■ In case where the number of illuminance sensors which affected by the lighting is one.

□Target illuminance＞Current illuminance

・The difference is more than 50 lx

If the degree of effect is large or medium – neighborhood G. If it is small – neighborhood F.

・The difference is less than 50 lx

If the degree of effect is large – neighborhood F. If it is medium or small – neighborhood E.

□Target illuminance＜Current illuminance

・The difference is more than 100 lx

If the degree of effect is large or medium – neighborhood C. If it is small – neighborhood B.

・The difference is less than 100 lx

If the degree of effect is large – neighborhood D. If it is medium – neighborhood C. If it is small - neighborhood B.

■ In case where the number of illuminance sensors which affected by the lighting is two or more.

□The illuminance sensor whose current illuminance is lower than target illuminance exists.

・The difference is more than 50 lx

Neighborhood G.

・The difference is less than 50 lx

Neighborhood F.

□The current illuminance of all the illuminance sensors has exceeded target illuminance.

・The difference is more than 100 lx

Neighborhood C.

・The difference is less than 100 lx

Neighborhood D.

4. Operational experiments

4.1 Structure of the experimental system

The hardware structure of the experimental system is comprised of 15 inverter controllable fluorescent lamps, 3 lighting control devices, and multiple movable illuminance sensors. Luminance of the lighting fixtures ranges from 30% to 100%.

4.2 Outline of experiments

In our experiments, we have implemented the proposed algorithm in lighting control equipment and verified the effectiveness of this algorithm in three experimental environments. The three types of experimental environments are seen in Fig.3.

Experment-1:

As shown in Fig.3, illuminance sensors A, B, and C are installed. Objective illuminance is 600, 800 and 700 lux, respectively.

Experiment-2:

At 350 seconds of searching, illuminance sensor C is moved to point D in Fig.3.

Experiment-3:

At 700 seconds of searching, 5 bulb color fluorescent lamps installed in the experiment room are fully (100%) turned on for simulating a condition as if daylight was streaming into the room. Further, at 1050 seconds of the search, the bulb color fluorescent lamps are turned off. Places for installing the bulb color fluorescent lamps are near the 11〜15 lighting points shown in Fig.3.

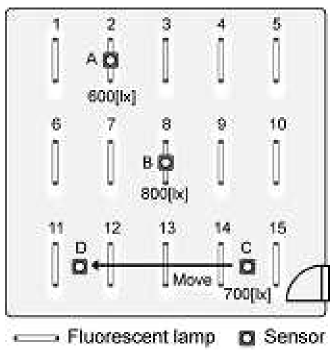

Fig.3 Experiment environment

4.3 Experimental results

4.3.1 Experiment-1 [No changes in the environment]

The history of illuminance is shown in Fig.4 and the history of power is shown in Fig.5. The horizontal axis and vertical axis of Fig.4 correspond to time and illuminance respectively. The vertical axis of Fig.5 indicates a percentage of electric power when full light power was at 100%.

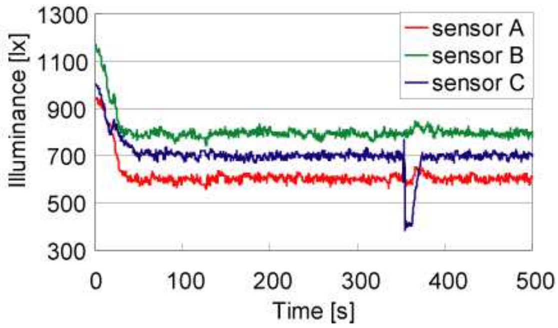

Fig.4 History of illuminance

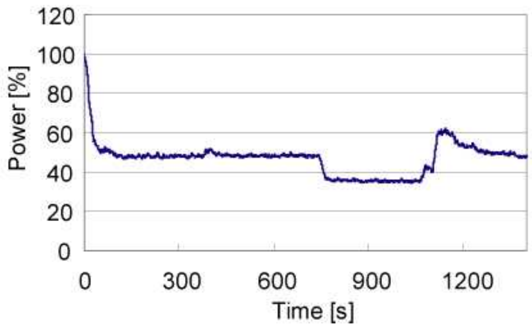

Fig.5 History of electricity

From Fig.4, we can confirm that the illuminance of each illuminance sensor A, B, and C reached 608, 807 and 742 lux, respectively about 35 seconds from the start of the experiment, converging to the objective illuminance. From Fig.5, we can see that consumed electric power has been saved by about 50% in this environment. In Fig.6, the values of luminance and illuminance are shown 140 seconds into the experiment. Here, luminance is indicated by a ratio against full light power.

4.3.2 Experiment-2 [When the illuminance sensor was moved]

From Fig.4, we can confirm that the illuminance sensor C has converged again to the objective illuminance about 20 seconds after its movement. Fig.7 shows the values of luminance and illuminance 500 seconds into the experiment. From the comparison between Fig.6, the before movement of the illuminance sensor, and Fig.7, the after movement, we can confirm that the luminance of the lighting fixtures having a stronger effect before the movement of the illuminance sensor has decreased and that luminance of lighting fixtures have a stronger effect after movement has increased. From these results, we can see that our proposed algorithm is corresponding to the movement of the illuminance sensor.

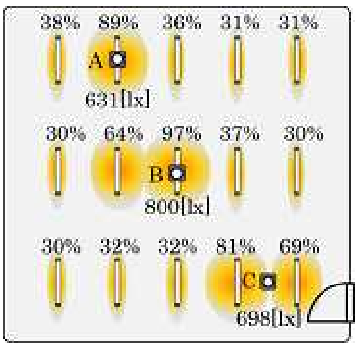

Fig.6 Steady state in experiment 1

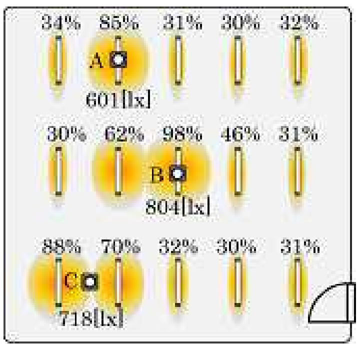

Fig.7 Steady state in experiment 2

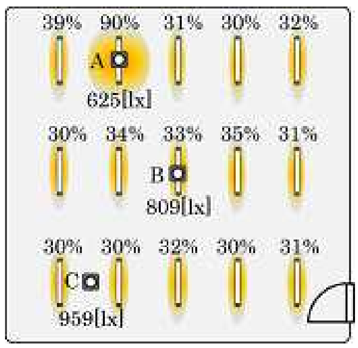

Fig.9 Steady state in experiment 3

4.3.3 Experiment-3 [Utilization of daylight]

Fig.8 shows the history of illuminance in experiment-3. After this Fig.8, the measured illuminance of illuminance sensors B and C have greatly increased after turning on the bulb color fluorescent lamps that are simulating daylight. Fig.9 shows a value of luminance and illuminance 900 seconds into the experiment.. From Fig.9, we can see that the lighting fixture located near the illuminance sensor is light at 30% of its maximum illuminance is the minimum in order to make the increased illuminance by daylight approach the objective illuminance. As a result, power consumption has been greatly reduced compared with Fig.5. From Fig.8, we can see that the illuminance of illuminance sensors B and C has greatly decreased from the objective illuminance after the bulb color fluorescent lamps were turned off, but it has again converged to the objective illuminance by about 20 seconds.

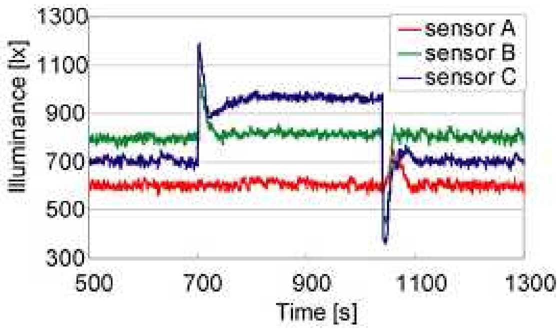

Fig.8 History of illuminance

5. Conclusions

In this research, we have formulated the degree of the effect of luminance and illuminance by using the luminance change of a lighting fixture and the illuminance change of an illuminance sensor. Then, we estimated the unknown parameters of the relational expression using the Kalman filter, and applied the obtained degree of effect to calculate the luminance change of the lighting fixture. We constructed the experimental system of intelligent lighting implementing the proposed algorithm and carried out operational experiments. As a result, we could provide an appropriate illuminance to any location. From these experiments, our proposed algorithm is found to be valid and effective in an intelligent lighting system. In the future, it will be necessary to verify the effectiveness of this new algorithm in various environments and also to consider cooperating with other applications for intelligent lighting systems.

REFERENCES

[1] Japanese Industrial Standards：JIS Z 9110 (1979)

[2] M.Miki, T.Hiroyasu, K.Imazato. Proposal for an intelligent lighting system and verification of control method effectiveness. *Proc IEEE CIS,* pp.520-525, 2004.

[3] M.Miki, T.Hiroyasu, K.Imazato, M.Yonezawa. Intelligent lighting control using correlation coefficient between luminance and illuminance. *Proc IASTED Intelligent Systems and Control,* Vol.497, No.078, pp.31-36, 2005.

[4] Yaakov Bar-Shalom, X.Rong Li, Thiagalingam Kirubarajan. Estimation with Applications to Tracking and Navigation : Theory algorithms and software. Wiley-Interscience. 584pp. 2001.