An Extraction Method of Influential Lightings for Illuminance Sensors on An Intelligent Lighting System in Large Office

Hisanori Ikegami, Sho Kuwajima, Mitsunori Miki and Hiroto Aida

1Department of Science and Engineering, Doshisha University, Kyoto, Japan
2Graduate School of Science and Engineering, Doshisha University, Kyoto, Japan

Abstract—We research and develop an intelligent lighting system to improve office workers comfort and to reduce the power consumption. We have introduced the intelligent lighting system to realize individual lighting environments into real office environments. According to target illuminance values, we reduce the power consumption drastically. We are considering to introduced the intelligent lighting system to the larger office. On the other hand, we have proposed the effective lighting control algorithm Adaptive Neighborhood Algorithm using Regression Coefficient:ANA/RC. In this method, to learn the positional relation of lightings and illuminance sensors using regression coefficient, luminous intensity is capable of appropriately changing. In the future, to introduce the intelligent lighting system to the larger office, we have to verify increasing learning time of the positional relation and accuracy of lighting extraction. The study proposes these verification and a new lighting extraction method without regression coefficient. We show that the proposed method is superior to previous method in the learning time and accuracy of lighting extraction.

Keywords: Lighting Control, Large Office, Regression Coefficient

1. Introduction

In recent years, continuing research into the office environment has identified that the office environment has a major influence on workers. Previous research has reported that improving the office environment can increase workers’ intellectual productivity and comfort[1], [2]. With regard to the lighting environment, it has also been reported that providing each worker’s desired brightness can raise intellectual productivity[3]. However, at present, the standard lighting design of Japanese offices features a desktop illuminance of 750 lx or greater in Japan. Consequently, this cannot be considered a lighting environment suited to each worker. Furthermore, it is also believed that desired illuminance differs by race and culture. For all these reasons, we have been researching into an intelligent lighting system in order to provide individual illuminance environments in our laboratory[4], [5]. An intelligent lighting system provides each user’s desired illuminance, and also gives energy saving.

Past applications of Intelligent Lighting Systems include a case using 35 lighting fixtures. Another example of an Intelligent Lighting System has been introduced at Kayabacho Green Building (Mitsubishi Estate Co., Ltd) completed in May 2013, which optimally controls lighting for the whole 7th and 8th floors, using 50 lighting fixtures per floor. Owing to their effectiveness, Intelligent Lighting Systems are now being considered for applications of even larger scales.

Current Intelligent Lighting Systems use a control algorithm called "ANA/RC" for optimizing their lighting patterns, which is based on the hill-climbing method. ANA/RC varies the luminance of each lighting appropriately for the level of influence by the lighting’s luminance on illuminance sensor measurements (hereinafter called the illuminance/luminance influence factor). Here, by lowering or turning off those lighting fixtures which little affect illuminance sensor measurements, these systems can realize a high standard of energy efficiency, while their energy efficiency largely depends on how accurately the system can learn illuminance/luminance influence factors. To dynamically learn illuminance/luminance influence factors, ANA/RC varies the luminance of each lighting minutely to the extent unnoticeable to human eyes and performs regression analysis based on the luminance change and illuminance change. However, while it 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, inhibiting the system to realize an energy efficient lighting pattern. To solve this problem for improving the system’s accuracy in learning illuminance/luminance influence factors by regression analysis, referring to the fact that relatively accurate regression coefficients are available for two lighting fixtures closest to an illuminance sensor, we developed a method to detect a group of lighting fixtures close to an illuminance sensor, using these two lighting fixtures and a lighting layout map (hereinafter referred to as "MAP method"). This method, as mentioned earlier, determines illuminance/luminance influence factors with reference to influence ranks. Using the MAP method enables the system to identify lighting fixtures close to illuminance sensors with much higher accuracy compared to a pre-existing method of ANA/RC. However, with a greater number of lighting
An optimal solution is derived. Control is performed by function value, and the transition process is repeated until solutions are accepted based on the changes in the objective function. The next step is taken based on the solution of the current step. An optimal solution is derived by generating the solution of this fashion, each user’s target illuminance can be provided based on illuminance data sent from illuminance sensors. In this way, lights learn the factor of influence to the illuminance sensors, making the brightness for each lamp the design variable, and the change in luminance for the lamp to converge to an optimum lighting pattern. Also, with the information of the lights, the system takes a longer time for regression analysis as well as for identifying two lighting fixtures close to an illuminance sensor.

By simulating lighting configurations with a minimum of 16 to a maximum of 400 lighting fixtures, this study examines the time required for detecting lighting fixtures close to illuminance sensors based on regression analysis, as well as the accuracy of detection results, and indicates problems in methods based on regression analysis. Furthermore, to identify lighting fixtures close to an illuminance sensor even in configurations comprising many lighting fixtures, a new method without using regression analysis will be proposed. It will be shown that the proposed method can identify lighting fixtures close to an illuminance sensor more correctly and quickly than regression analysis-based methods.

2. Intelligent lighting system

2.1 Overview of the intelligent lighting system

The intelligent lighting system, as indicated in Fig. 1, is composed of lights equipped with microprocessors, portable illuminance sensors, and electrical power meters, with each element connected via a network. Individual users set the illuminance constraint on the illuminance sensors. At this time, each light repeats autonomous changes in luminance to converge to an optimum lighting pattern. Also, with the intelligent lighting system, positional information for the lights and illuminance sensors is unnecessary. This is because the lights learn the factor of influence to the illuminance sensors, based on illuminance data sent from illuminance sensors. In this fashion, each user’s target illuminance can be provided rapidly.

2.2 Lighting control algorithm

The hill-climbing method is an algorithm where the optimal solution is derived by generating the solution of the next step based on the solution of the current step. Solutions are accepted based on the changes in the objective function value, and the transition process is repeated until an optimal solution is derived. Control is performed by taking the lightness of lighting (the luminous intensity) to be the design variable, and taking the sum of the difference between current and target illuminance and electric power consumption to be the objective function. Furthermore, in ANA/RC, differences in lightness that a light exerts on the illuminance meter are learned by regression analysis, and luminous intensity is appropriately changed in response to the degree of exertion [4], [6], [7]. By using this process, solutions can be quickly derived. Hereafter, the lightness difference a light exerts on an illuminance meter will be called ‘influence’.

Intelligent lighting system aims to adjust the illuminance to equal or greater than the target illuminance for the location where the sensors are installed, and autonomously finds the lighting intensity to minimize the amount of electrical power used for lighting. This illuminance must be formulated as an objective function. The objective function for each lamp is shown in Eq. 1.

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

\[
g_{ij} = \begin{cases} 0 & (L_{c,j} - L_{t,j}) \geq 0 \\ R_{ij} (L_{c,j} - L_{t,j})^2 & (L_{c,j} - L_{t,j}) < 0 \end{cases}
\]

\[
R_{ij} = \begin{cases} r_{ij} & r_{ij} \geq \text{Threshold} \\ 0 & r_{ij} < \text{Threshold} \end{cases}
\]

\[
f: \text{Objective function, } i: \text{light number, } m: \text{Number of light} \\
p: \text{Number of illuminance sensors, } w: \text{Weighting factor} \\
P: \text{Amount of consumed electrical power} \\
L_c: \text{Current illuminance, } L_t: \text{Target illuminance} \\
r: \text{Correlation coefficient, } \text{Threshold}: \text{Threshold value}
\]

Making the brightness for each lamp the design variable, we aim to minimize the \( f \) in Eq.1. \( P \) consists of the amount of consumed power \( P \), and \( g_{ij} \), which is derived by multiplying by the correlation coefficient \( r_{ij} \) by the difference between the current illuminance \( L_c \) and the target illuminance \( L_t \) entered by the user. The correlation coefficient \( r_{ij} \) accounts for the change in luminance for the lamp \( i \) and the change in illuminance for the illuminance sensor \( j \). If the correlation is less than or equal to the threshold value, it is multiplied by 0. \( g_{ij} \) is added only if the current illuminance has fallen below the target illuminance. Thus, the accuracy to which the target illuminance can be met is improved by narrowing down the optimization target for the sensor with the highest correlation, that is, for the sensor which is located nearby. Also, \( g_{ij} \) is multiplied by a weight \( w \), and the value of this weight \( w \) determines whether priority is given to minimizing, either the constraint conditions on the target illuminance, or the amount of consumed power.
2.3 Issues in large-scale lighting configurations

The effectiveness of Intelligent Lighting Systems for increasing workers’ comfort and reducing power consumption has already been recognized, and verification experiments are underway at several offices in Tokyo. To date, there have been applications using 35 lighting fixtures and 50 lighting fixtures, and applications of even larger scales are under consideration. Applications to large-scale lighting configurations will require considerations on many factors such as increased physical wiring to lighting fixtures and illuminance sensors, delay in the acquisition of illuminance data from illuminance sensors, delay in the transmission of control signals to lighting fixtures, or applicability of the lighting control algorithm. This study will examine the applicability of conventional methods using regression analysis (the ANA/RC and MAP methods) to large scale lighting configurations, particularly concerning the detection of influential lighting fixtures for each illuminance sensor: here, we will examine the time required for accurate detection of influential lighting fixtures, and indicate problems in the detection of influential lighting fixtures by regression analysis.

3. Examination of the accuracy detecting illuminance sensors in large office

3.1 Experiment summary

Experiments simulating nine types of lighting arrangements (4 rows x 4 lines, 6 rows x 6 lines ... and 14 rows x 14 lines) were conducted. Out of the simulated configurations, Fig. 2 shows the arrangements of 4 rows x 4 lines and 6 rows x 6 lines. In all lighting configurations simulated here, the illuminance sensor was positioned right under the lighting in the third row and third line. To calculate illuminance in the simulation, a point-by-point method was used. A point-by-point method is a simple method of calculating illuminance at an illuminated point from the luminance of the light source based on the distance between the light source and the illuminated point. In order to sufficiently meet illuminance requirements by workers, four to six lights need to be chosen for each illuminance sensor. For this, in the experiment, the detection of nearby lighting fixtures by ANA/RC was considered to be successful when four or more lights out of the nine closest to the illuminance sensor show the highest regression coefficients. In the MAP method, if the two lights closest to the sensor are identified, then four to six lights can be selected based on the lighting layout map. Hence, for the MAP method, the detection of influential lighting fixtures was deemed successful if the regression coefficients for at least two out of the nine closest lights were highest.

3.2 Examination of the time required for detecting in previous method

We measured the time required to successfully detect lighting fixtures close to illuminance sensors in configurations with a small number of lighting fixtures and a large number of lighting fixtures. In conditions assuming these configurations, 100 times of simulation experiments were conducted. Figures 4 and 5 show the time required for learning regression coefficients, and success rates in the detection of influential lighting fixtures in 4x4 and 10x10 lighting conditions respectively.

Fig. 3 shows that in a small lighting configuration, the MAP method requires only one minute (30 steps) for detecting lighting fixtures close to the illuminance sensor. We can see from Fig. 4, however, that even in the MAP method, the nearby lighting fixture detection accuracy does not reach 100% before 12 hours (21600 steps). When a single regression analysis is to be conducted, the larger the number of lighting fixtures is, the longer it will take to calculate regression coefficients correctly even for the two lighting fixtures closest to the illuminance sensor. When a multiple regression analysis is to be conducted, the number of the data needed for a regression analysis increases as the number of lighting fixtures (the number of explanatory variables) increases: because at least as many steps as the number of lighting fixtures (explanatory variables) are needed until a regression analysis is available, it is impractical for a large scale lighting configuration. In order to prevent discomfort
or mistrust of the system in workers, it must be able to quickly detect influential lighting fixtures and realize the target illuminance. When introducing an Intelligent Lighting System in a real office, we first determine the time required for accurate detection of influential lighting fixtures while preventing discomfort among workers, through repeated experiments and dialogues with users at the real office, before configuring the system’s regression-analysis based learning time. To realize an application in a real office configuration, quick and accurate detection of influential lighting is essential.

3.3 Verifying the accuracy of short-time detection of nearby lighting fixtures

Simulation experiments in nine lighting conditions were conducted by repeating 100 tests each, using a regression-analysis-based learning time in 60 steps (about two minutes), and the accuracies of the detection of lighting fixtures close to an illuminance sensor were compared between different conditions. The learning time of 60 steps (about two minutes) is based on the setting adopted by the Intelligent Lighting System at Futako Tamagawa Catalyst BA in August 2012. The success rate in the detection of influential lighting fixtures in different lighting conditions is shown in Fig. 5.

As you can see from Fig. 5, as the number of lighting fixtures increases, the success rate goes down. Although the regression coefficient for an illuminance sensor close to a lighting fixture can be obtained with a relatively close gap from the true value, a regression coefficient for an illuminance sensor distant from a lighting fixture is often far from the true value, sometimes exceeding the coefficient for a sensor close to the lighting: ANA/RC calculates a regression coefficient by randomly varying the luminance of lighting fixtures by minute scales, but when illuminance change on an illuminance sensor happens to be similar to luminance change on lighting fixtures distant from the sensor, the regression coefficient for the lighting distant from the sensor may be calculated higher than it really is. The probability of this phenomenon is higher when the number of lighting fixtures is greater, and that is considered to be the cause of the decline of the detection success rate with the increase in the number of lighting fixtures. In the case of the Intelligent Lighting System installed at Futako Tamagawa Catalyst BA using MAP method, the system prevents wrong detection by trying the learning process again if the two lights detected as most influential are found distant from the sensor on the lighting layout map. Specifically, in the case of a configuration with 36 (6 x 6) lights in Fig. 5, if the initial accuracy is 76%, another two learning trials (taking about 6 minutes including the initial learning) can boost the success rate to 98.6%\(^1\). In a configuration having not more than 50 lighting fixtures, such as the current office applications of an Intelligent Lighting System, detecting influential lighting fixtures has been possible with a practical accuracy by finding wrong detections using the MAP method. However, in a configuration with 10 x10 lights, the success rate remains as low as 57.8% after another two learning trials.

From these results, an accurate identification of influential lightings takes much time even with a MAP method; the larger the number of lighting fixtures is, the more difficult it is to accurately identify lighting fixtures close to an illuminance sensor in a short time. Now it is essential to establish a method which can identify lighting fixtures near an illuminance sensor within a learning time as short as in the existing real office applications of Intelligent Lighting Systems, even when the number of lighting fixtures increases.

4. Identification of lighting by scanning illuminance sensor coordinates

Here, we propose a method without using a regression coefficient to identify lighting fixtures close to an illuminance sensor in a large-scale lighting configuration. In this method, lights are divided into row groups and line

\(^1\)\(p+(1-p)*p+(1-p)*(1-p)*p\) (when the success probability is p)
Fig. 6: Illuminance sensor detecting method on the coordinate groups, and the luminance settings of these groups are varied by degrees unnoticeable to human eyes one group after another[8]. The system varies the luminance of lights in each group to a certain degree, and considers the lighting group causing the greatest variation in sensor illuminance to be the group closest to the illuminance sensor. By finding an intersection of the groups causing the greatest sensor illuminance change, the system identifies the lighting fixtures close to the illuminance sensor. Fig. 6 shows the concept of this method. Also, the flow of the identification of nearby lighting fixtures is shown below.

1) All lights are divided into row groups and line groups
2) The system obtains the current illuminance on each illuminance sensor
3) The system changes the luminance of all lights in a lighting group by $\Delta L$ which is the same value for all groups.
4) The system acquires the illuminance data from all illuminance sensors and calculates illuminance changes.
5) For all lighting groups, steps from (2) to (4) are repeated.
6) Based on the illuminance changes calculated in step (4), take an intersection of the lighting groups of the greatest illuminance change.
7) With reference to the illuminance change of the group a detected lighting belongs to, give it a rank of influence on the illuminance sensor.

Concerning step (3), based on the minimum noticeable change ratio[8], the system varies the luminance by magnitudes unnoticeable to human eyes. Because the value may depend on the lighting arrangement, distance between the ceiling and the desk surface and the lighting’s radiation characteristics, â ´L ˛ EL needs to be determined through experiments in a real configuration. Concerning step (7), as shown in Fig. 6-(c) and Fig. 6-(d), for example, the lighting picked as an intersection of the largest illuminance change row group and line group is ranked the first, whereas the lighting picked as an intersection of the largest illuminance change row group and the second-largest illuminance change line group is ranked the second. Using this way, lights can be ranked in terms of distance from each illuminance sensor. By determining illuminance/ luminance influence factors based on the ranking of lights close to each illuminance sensor, power consumption can be saved as much as by an Intelligent Lighting System already introduced in real office configurations. Furthermore, the time required for picking nearby lighting fixtures in this method is for (the number of lights per row + the number of lights per line) steps regardless of the total number of illuminance sensors. Hence, even in the case of a configuration with 30 x30 lights, influential lighting fixtures can be picked in only 60 steps (or about 2 minutes). Since the time required for picking nearby lighting fixtures is in a linear relation with the number of lighting fixtures, this method is more suitable for large scale lighting configurations than conventional methods which are subject to a non-linear increase in the time required for accurately picking nearby lighting fixtures.

On the other hand, real-office applications need to take into consideration the effect of factors other than the luminance of the lighting, such as people’s shadows or change in natural light, on the illuminance detected by a sensor. Since the illuminance given by the luminance of lighting fixtures is in inverse relation to the second power of the distance, the illuminance change given by an illuminance sensor by each lighting group is larger in groups closer to the illuminance sensor, and smaller in groups farther from the sensor. The illuminance change from the effects of factors other than the lighting such as human shadows and natural light can be detected by comparing illuminance changes between adjacent lighting groups. Furthermore, concerning step (3), the search time may be even shortened by simultaneously changing the luminance of two groups of lighting fixtures which are distant enough to be mutually free from interference. This method has already been used in an Intelligent Lighting System installed at Futako Tamagawa Catalyst BA, which is now in the process of disturbance detection and verification of search time reduction.
5. Illuminance convergence and lighting pattern verification experiment

A verification experiment was conducted to demonstrate the effectiveness of an Intelligent Lighting System incorporating the proposed method. In the experiment, a small number of illuminance sensors were used to make it easier to verify whether lighting fixtures in appropriate positions are turned on. For the experiment, a configuration using 30 lighting fixtures and three illuminance sensors as shown in Fig. 8 was used. The experiment was conducted in a space measuring 7.2m x 6.0m x 1.9m, equipped with cool white fluorescent lamps (FHP45EN) made by Panasonic Corporation variable between 30% and 100%.

An illuminance convergence experiment was conducted in an experimental configuration shown in Fig. 7. Concerning the ANA/RC and MAP method, 60 steps (about 2 minutes) were provided for the system’s learning by regression analysis. This is the same as the learning time used in existing Intelligent Lighting Systems adopted in real offices. Between a method using regression analysis and the proposed method, the illuminance histories and lighting statuses of each lighting were compared. Fig. 9 shows the illuminance history of each illuminance sensor with ANA/RC; Fig. 10 shows the illuminance history of each illuminance sensor with a MAP method; and Fig. 11 shows the illuminance history of each illuminance sensor with the proposed method. For information, each lighting control step takes about two seconds. Fig. 12 shows the status of lighting after 300 steps in each method.

As one can see from Fig. 8 and Fig. 9, there is no significant difference in illuminance history between the methods which detect influential lighting fixtures based on regression analysis. However, as Fig. 11 shows, some lighting fixtures distant from the illuminance sensor are turned on in the ANA/RC method while only those near the sensor are turned on in the MAP method, realizing an efficient lighting pattern in terms of energy consumption. The proposed method also realizes an energy efficient lighting pattern like the MAP method. Next, as you can see from Fig. 10, the proposed method has completed the detection of influential lighting fixtures in eleven steps, which is faster than in methods based on regression analysis. If the illuminance/ luminance influence factor is to be learned in ten steps (about 20 seconds) in a convergence experiment using a conventional method, according to Fig. 5 in Section 3.2, the detection success rate will be 7% in the MAP method and 1% in the ANA/RC method. Unless influential lighting fixtures are successfully detected, it will never be easy to realize a target illuminance nor energy-efficient lighting patterns. From these results, it has been demonstrated that the proposed method is able to detect lighting fixtures close to an illuminance sensor more quickly and accurately than conventional methods.

With a method using regression analysis, the system can learn the illuminance/ luminance influence factor while controlling convergence to the target illuminance. On the other hand, with the proposed method, the system cannot simultaneously pursue the two processes of learning the illuminance/ luminance influence factor and controlling convergence to the target illuminance. However, as one can see from Fig. 10, the illuminance variation in the learning period for detecting influential lighting fixtures is so small as to be unnoticeable to workers [8] that the short period of the learning phase without illuminance convergence control is
considered to cause no problem.

For information, if the proposed method is used in a configuration with 10 x10lights, influential lighting can be detected in 20 steps (about 40 seconds). For comparison, Fig. 12 shows the accuracy of detection in other methods in an illuminance/ luminance influence factor learning time of 20 steps in a configuration with 10 x10lights.

Because it is not easy to reproduce by simulation all disturbance factors plausible in a real office configuration, the detection accuracies shown in Fig. 13 are experimental values from simulations. Currently, a verification experiment concerning disturbance detection and search time reduction is underway with the Intelligent Lighting System installed at Futako Tamagawa Catalyst BA. Furthermore, we plan to build an Intelligent Lighting System involving worker movements with more than 50 lighting fixtures, which will be experimented in another verification experiment at a real large-scale office.

Fig. 10: Illuminance History in Proposed Method

Fig. 11: Status of Lightings (300 steps)

6. Conclusion

In this study, we demonstrated that detecting influential lighting fixtures close to an illuminance sensor by regression analysis requires much time for accurate lighting detection when the number of lighting fixtures is greater. In view of this fact, in order to quickly detect lighting fixtures close to an illuminance sensor even in a configuration with many lighting fixtures, we developed a new method not relying on regression analysis. The proposed method divides lighting fixtures into groups, and detects lighting close to an illuminance sensor based on the illuminance change in each lighting group and the illuminance change on the illuminance sensor. Verification experiments have demonstrated that the proposed method can shorten the time required for detecting lighting fixtures compared to regression analysis methods, and enables correct detection of nearby lighting fixtures.

References