INTELLIGENT LIGHTING CONTROL USING CORRELATION COEFFICIENT BETWEEN LUMINANCE AND ILLUMINANCE

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ABSTRACT

An intelligent lighting system which provides required illumiancne at an appropriate location is proposed. This system does not have the centralized control device and also it is controlled by each intelligent lighting's autonomous operation. Also the intelligent lighting system can contribute to energy saving. In this research, a new algorithm is proposed. For rapid converges it uses the correlation coefficient between the illuminance at given locaion and the luminance of each light. We actually construct an autonomous distributed experiment system and verification tests were conducted using the proposed control method. The results showed that the various illuminance sensors converged to the preset target illuminance. We also confirmed that the algorithm can respond adaptively to environmental changes and it is effective to energy saving.

KEY WORDS

Intelligent, lighting systems, autonomous distributed control, energy saving, intelligent system, cofficient crrelation.

1 Introduction

In recent years, electric appliances, automobiles, airplanes and a variety of other systems have become more intelligent, through autonomous control of the system's own operation to suit the user and the environment. This alleviates the load on human beings[1].

Although systems in the real world are becoming more intelligent in this way, intelligence has not been applied to lighting systems, which are a necessary and indispensable part of human life. And also, artificial lighting is one of the major electricity-consuming items in many non-domestic buildings, accounting for 20-30% of total electricity load[2]. For example, it is impossible to achieve a lighting pattern other than that imposed by the electrical wiring at the time of design, and it is impossible to automatically and locally realize the appropriate illuminance. Recently, technology has been developed for individually controlling the luminance of various lights by connecting the lights to a network, and systems with a high-level human-interface have appeared [3][4][5][6]. And also, many new technologies which conserves energy using daylight and the theory of electric-lighting saving due to daylight is well understood[7]. For example, time switching and photo-electric controls have been developed to improve the efficient use of daylight and it can give excellent energy savings[8][9][10]. However, many problems still remain. For example, it is impossible to automatically provide the appropriate illuminance to an arbitrary location, or to allow other lighting to compensate illuminance in response to the failure of a lighting device. Other problems include: the inability to flexibly respond when lighting or lighting sensors are added, or when room partitions are changed.

On the other hand, a new lighting system called intelligent lighting system[11], which can resolve these problems, is proposed. We used an autonomous distributed optimization algorithm, based on the stochastic hill climbing method, as the lighting control method before. This control method is useful for environments with less than some ten lightings. However, the convergence of illuminance to target illuminance becomes very slow. Therefore, it is assumed that the estimation of distance between light and illuminance sensor can improve the speed of convergence. The distance can be estimated from the correlation coefficient between the luminance of the light and the illuminance mesured by illuminance sensor.

To realize advanced intelligent lighting system, the algorithm which controls the system is important as well as the completeness of the hardware. In this research, a new control algorithm, which is based on the concept of autonomous distributed control, using correlation of illuminance and luminous intensity is proposed.

2 What is an Intelligent Lighting System?

2.1 Overview of intelligent lighting system

The term "intelligent lighting system" refers to a system where multiple lighting fixtures are connected to a network, and users needs are met by cooperation of the various lighting fixtures. The following describes the features of the intelligent lighting system.

2.1.1 Autonomous Distributed Control

In the intelligent lighting system, there is no element with control over the entire system. Illuminance at each location is controlled by having each light perform learning operation. There is no central control unit, so the system has high robustness against malfunction, and high reliability can be achieved even in large-scale buildings.

2.1.2 Achieving Autonomous Lighting Control

In today's illumination systems, only the limited lighting pattern can be realized due to the wiring pattern. However, with the intelligent lighting system, it is possible to realize an arbitrary lighting pattern which is not dependent on the wiring of lights. Also this intelligent lighting system, the user simply sets the target illuminance, and the system can automatically determine the necessary luminance, without making the user aware of the location of lights, and thus can provide the appropriate illuminance to the appropriate location.

2.2 Configuration of the Intelligent Lighting System

The intelligent lighting system is configured by connecting multiple intelligent lighting fixtures and multiple movable illumination sensors and power meters to a network. The term "intelligent lighting fixture" means lighting which has a controller called a learning device. This makes it possible for each individual lighting fixture to operate autonomously. Fig.1 shows the configuration of an intelligent lighting system.

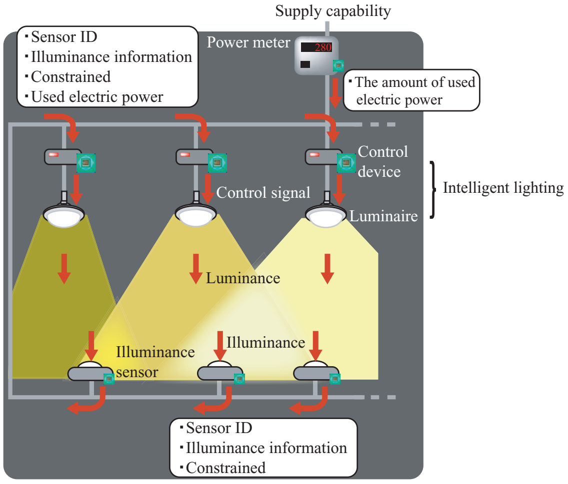


Figure 1. Configuration of the intelligent lighting system

2.3 Intelligent Lighting System Control

The intelligent lighting system is controlled using the autonomous distributed method. Each intelligent lighting fixture controls illuminance by autonomously adjusting luminance. The control process is described below.

1. Initialize the intelligent lighting system, provide the goal of "minimizing the amount of power used" to the learning devices, and provide the constraint of "setting the illuminance of each illuminance sensor at or above a certain value" to the illuminance sensors.
2. Each illuminance sensor detects the current illuminance.
3. Each illuminance sensor sends its target illuminance and current illuminance to the network.
4. Each intelligent lighting fixture connected to the network takes in the amount of power used, and the target illuminance and current illuminance of each illuminance sensor.
5. The learning device of each intelligent lighting fixture controls luminance based on the illumination control algorithm proposed in this research, using the amount of power, and the current and target illuminance of each sensor.
6. By repeating Steps 2 to 5, the system constantly senses environmental information, and provides control so that goal is satisfied.

Using the above process, each inteligent light can autonomously performs lighting control to satisfy goals and illuminance constraints. By constantly sensing environmental information, the system can respond to addition or malfunction of lights, and addition and movement of illuminance sensors.

3 The Configuration of Autonomous Distributed Experiment System

The autonomous distributed experiment system, is actually built based on intelligent lighting systems concept. The configuration of the experiment system is 15 inverter controllable fluorescent lights, 15 lighting control devices, multiple movable illuminance sensors. Inverter control is a technology wherein luminance is adjusted by arbitrarily varying the duty ratio of a digital waveform. All of these hardware are connected to one network. In this experiment system the power meter, which measures the amount of used electricity is not included. The sum of each light's luminance intensity is substituted as the amount of used electricity. In addition, in this experiment system there is no central control element with controls over the entire system. Each light has it's own lighting control device so this can achieve the autonomous distributed control system.

4 Adaptive Neighborhood Algorithm using Correlation Coefficient

In this section, new algorithm that can search effectively by estimating the distance of the light and the sensor from the correlation between luminance and illuminance intensity, is proposed.

4.1 Overview of Adaptive Neighborhood Algorithm using Correlation Coefficient

The proposed algorithm calculates the correlation from "the amount of luminous intensity changed" and "the amount of illuminance intensity changed". From now on, proposal algorithm is called Adaptive Neighborhood Algorithm using Correlation Coefficient as ANA/CC. The flow chart of this algorithm is shown in Fig.2. The control process of this algorithm is shown below.

1. Perform initialization and set the initial parameters.

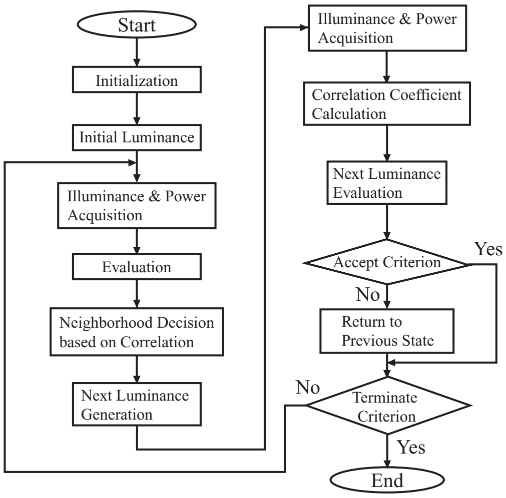


Figure 2. Adaptive Neighborhood Algorithm using Correlation Coefficient

2. Switch on all fluorescent lights at their initial luminance.
3. Calculate the objective function from information of each illuminance sensors (Sensor ID, current illuminance, and target illuminance) and amount of electricity used.
4. An appropriate neighborhood range is determined based on the correlation.
5. Next luminance is generated randomly with in the neighborhood, which is determined at (4), and turn on each light with the new luminance.
6. Get new information of illuminance sensors and new amount of electricity used.
7. Calculate the correlation from the new illuminance and new luminance.
8. Calculate the objective function from new illuminance and amount of electricity using.
9. If the objective function value is satisfactory, set that luminance and return to step(3).
10. If the objective function value worsened in step (8), cancel the pervius of luminance and retrun to step(3).

By performing the above operation, it can converge to the target illuminance and to a power saving state.

4.2 Further Details about ANA/CC

4.2.1 Correlation Between Luminance and Illuminance

In order to converge to the target illuminance and minimize electric power in short time, estimating the distance of lights and illuminance sensors is thought to be effective in lighting control algorithm. In proposed algorithm a correlation coefficient is used to estimate the distance autonomously and dynamically. The amount of luminance changed and the amount of illuminance changed is used to calculate the correlation. In other word, ”the difference between current luminance and next luminance” and ”the difference between the current illuminance and next illuminance” is used to calculate correlation coefficient. This will enable us to estimate the distance correctly.

4.2.2 About the Correlation Coefficient and the Distance

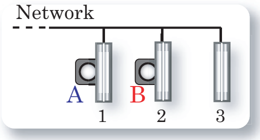


Figure 3. Distance between light and sensors

Fig.3 shows the example of the distance of lights and illuminance sensors. For light 1, the correlation with sensor A becomes high and the correlation with sensor B is low . For light 2, the correlation with sensor A becomes low, and the correlation with sensor B is high. For light 3, the correlation with both sensors becomes low because they are at the distant position from light 3. If the distance can be estimated by the correlation correctly, lights which does not have sensor in near distance should lower the luminance. And lights which have sensors in near distance should change the luminance to appropriate luminance intensity to satisfy the target illuminance.

4.2.3 Three Types of Changes in Luminance

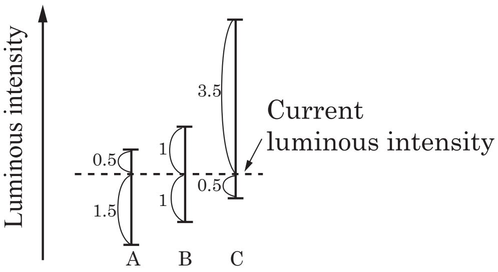


Figure 4. Three neighborhood ranges

In ANA/CC, the luminance of each light is changed randomly with in a given range, and this range is called a neighborhood range in ANA/CC. As you can see in Fig.4, there are three types of neighborhood range in ANA/CC and it is used to generate next luminance. The values in Fig.4 shows the relative rate of each neighborhood size. These upper and lower value of neighborhood range is estimated experimentally. Neighborhood range A attaches the importance to lower the luminance from current luminance to converge to target illuminance. Neighborhood range B generates the next luminance equally in the upper and lower sides, and it is used to adjust the luminance. Neighborhood range C attaches the importance to increase the luminance intensity from current luminance. Only the neighborhood B has been used for the conventional control algorithm so far.

4.2.4 Determination of Neighborhood Range Process

In ANA/CC there are three types of neighborhood range as shown in Fig.4. To select one of the neighborhood ranges adaptively, the correlation coefficient between luminance and illuminance is used. Then next luminance is generated randomly within the neighborhood range. The process of the determination of neighborhood range is shown below.

1. Each light calculates the correlation coefficient with all the illuminance sensors in the room.

$$\begin{cases} A & r_i < threshold \\ B & r_i \geq threshold\, and\, Lt_i \leq Lc_i \\ C & r_i \geq threshold\, and\, Lt_i > Lc_i \end{cases}$$

2. i is illuminance sensor's number, r is correlation coefficient, Lt is target illuminance, and Lc is current illuminance.

   If all the correlation coefficients are less than the threshold, neighborhood range A is selected. If more than one correlation coefficient is higher than the threshold and the values of all the sensors current illuminance are higher than the target illuminance, neighborhood B is selected. If more than one correlation coefficient is higher than the threshold and more than one current illuminance of the sensor are less than the target illuminance, neighborhood range C is selected. The value of the threshold is determined by pre-experiment.

From these rule, the lights which have the illuminace sensors in near distance should change the luminance properly for that sensor and the light which does not have illuminance sensor in near distance should decrease the luminance to minimum luminance.

4.2.5 Objective Function Used in the Proposed Algorithm

The goals of the intelligent lighting system are to bring the illuminance close to the target illuminance for each sensor, and to minimize electric power. In other Words, these goals must be properly formulated in the objective function. The objective function used in this algorithm is expressed in Equation.(1).

$$\begin{aligned} f &= P + w\sum_{j=1}^{n} g_j \qquad (1) \\ P &= \sum_{i=1}^{m} Cd_i \\ g_j &= \begin{cases} 0 & (Lc_j - Lt_j) \geq 0 \\ R_j(Lc_j - Lt_j)^2 & (Lc_j - Lt_j) < 0 \end{cases} \\ R_j &= \begin{cases} r_j & r_j \geq threshold \\ 0 & r_j < threshold \end{cases} \end{aligned}$$

In ANA/CC, the goal is to minimize f in Equation.(1). f is the sum of g_j, which indicates the illuminance difference between the current illuminance Lc and target illuminance Lt, and P is the amount of electric power used. r indicates correlation coefficient. For electric power P, use the sum of each lighting's luminance intensity Cd. The luminance has a linear relationship with the energy consumed, and here it is taken to be the power used by each light. g_j is added only if the illuminance difference is negative. In other words, the light increase the luminance rapidly if the current illuminance is less than the target illuminance. If the correlation coefficient is less than threshold, the illuminance difference is not taken account, thus speed of convergence will be improved. The weighting factor w determines the priority between adjusting the target illuminance, or minimizing the electric power.

5 Experiment using ANA/CC

5.1 Outline of the Experiment

Experiments were conducted using the following patterns to confirm that proposed intelligent lighting system can satisfy the target illuminance and minimize the electric power using ANA/CC. Also we verified that ANA/CC can estimate the distances of the lights and the illuminance sensors from the correlations.

The parameters used in the experiment are shown in Table.1.

Table 1. Experiment parameters

Number of fluorescent lamps	15
Number of illuminance sensors	3
Target illuminance [lx]	750,800,600
Distribution of light increase decrease(Pattern A) [%]	+2,+1,0,-1,-2,-3, -4,-5,-6,-7,-8
(Pattern B) [%]	±5,±4,±3,±2,±1,0
(Pattern C) [%]	+17,+16,+15,$\cdots$ +1,0,-1,-2,-3
Maximum luminous [%]	100
Minimum luminous [%]	30
Initial luminance [%]	100
Weight(w)	1.0
Maximum threshold value	0.5
Minimum threshold value	0.3
Number of data for the correlation coefficient	50

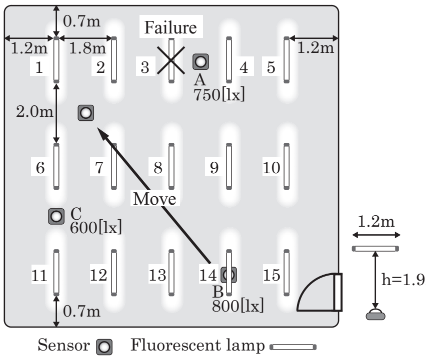


Figure 5. Experiment environment

- **Experiment-1**:When the environment is fixed
  The target illuminance of the illuminance sensor was set to: 750[lx] for sensor A, 800[lx] for sensor B, 600[lx] for sensor C. The arrangement of illuminance sensors are shown in Fig.5.
- **Experiment-2**:When the illuminance sensor is moved
  The illuminance Sensor B is moved from the location in Experiment1 to the center position between Lights1, 2, 6, and 7.

- **Experiment-3**:When the light is failed
  Light3 is failed with the same location of the sensors as in Experiment-1.

5.2 Result of the Experiment using ANA/CC

5.2.1 Experiment-1:When the Environment is Fixed

This section describes the experiment result when the environment was fixed. Figs. 6, 7 and 8 show the historys of the illuminance at each illuminance sensor, the electric power and luminance of lights 4, 6, 9 and 12.

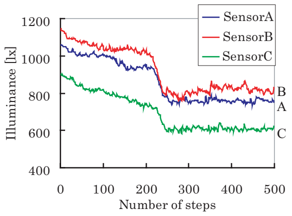


Figure 6. Illuminance

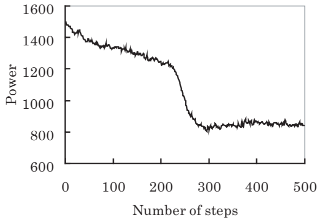


Figure 7. Power

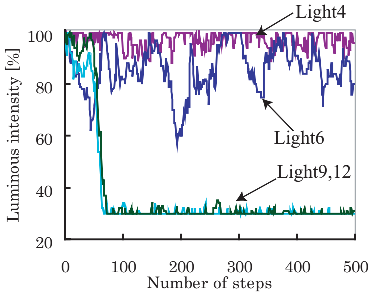
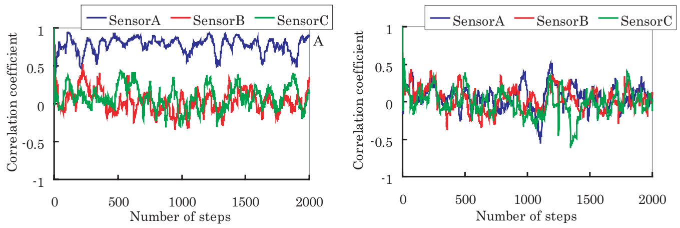


Figure 8. Luminous intensity history

As you can see from Fig.6, after the start of the experiment, the initial illuminance decreases and when the number of searching step is 250 (2 minutes), the illuminance at illuminance sensors A, B and C becomes, 776, 792 and 597[lx], so the illuminance converges to the value close to the target illuminance. As you can see in Fig7, as the time proceeds the electric power decreases. From Fig.8, the luminance of lights 4 and 6 are high because they are in the near distance of the illuminance sensor. The luminance of lights 9 and 12 are at the minimum luminance because they don't affect any sensor.



a) Lamp4

b) Lamp9

Figure 9. Correlation coefficient between the light and the sensors

Figs. 9-a and 9-b show the historys of the correlation coefficient of light 4 and 9. Sensor A is near light 4 and any sensor does not exist near light 9. Fig.9-a, shows that only sensor A is at high value. Fig.9-b shows that correlation coefficient is low for all three sensors. In other words, the result of correlation coefficient between luminance and illuminance can be used to estimate the distance of the lights and the illuminance sensors.

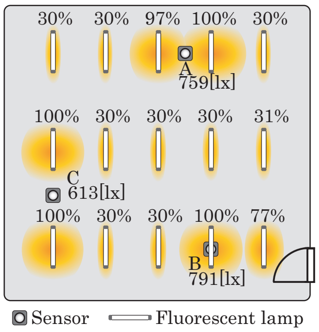


Figure 10. Luminous intensity[%] and illuminance in the stady state

The steady state of this experiment, is shown in Fig.10. The values of the illuminance at each sensor are 759, 791 and 613[lx], so they converge to values close to the target illuminance. Also, the luminance of the lights which have the sensor in near distance are very high, and the luminance of the lights which does not affect any of the sensor are at minimum luminanse. From these result, ANA/CC can be thought to be valid.

5.2.2 Experiment-2: When the Sensor is Moved

This section describes the experimental result when the illuminance sensor was moved. Fig.11 showes the historys of the illuminance for each illuminance sensor.

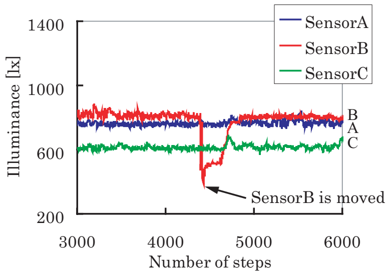


Figure 11. Illuminance history

In Fig.11, the value of illuminance sensor B, becomes much less than the target illuminance when it is moved. This happened because sensor B is moved to the darker location of the room. However, after about 400 steps (3 minutes) the illuminance of illuminance sensor B reached back to the target illuminance.

Fig.12 shows the luminance before sensor B is moved and Fig.13 shows the steady state after sensor B is moved. In the steady state, the illuminance of each sensor becomes 761, 809 and 600[lx], so the algorithm has almost converged on the target illuminance. By comparing Figs.12 and 13, we can see that luminance was increased at lights 1, 2, 6, and 7(at the location where sensor B is moved to), and the luminance of lights 13, and 14 decreased because they no longer affect any illuminance sensors. From this

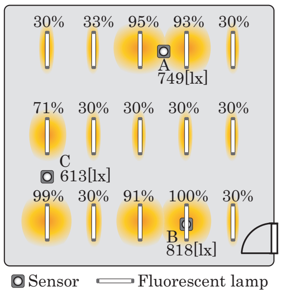


Figure 12. Before sensor B is moved

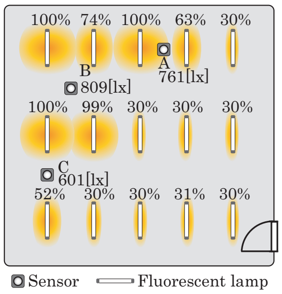


Figure 13. Steady state after sensor B is moved

experimental results, ANA/CC can respond to the movement of the illuminance sensor.

5.2.3 Experiment-3: When the Light 3 is Failed

This section describes the experimental result when the light 3 is failed. Fig.14 show the historys of the illuminance for each illuminance sensor.

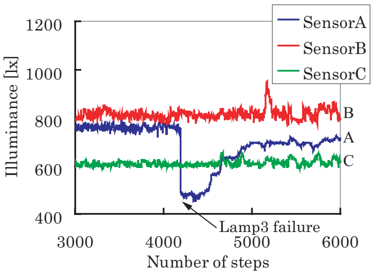


Figure 14. Illuminance history

As you can see in Fig.14, when the light 3 is failed, the illuminance of sensor A decreased to 470[lx] and after about 800 steps (6 minutes) from the failure the illuminace of sensor A reached 700[lx]. However, it did not reach to 750[lx] which is the target illuminance. This is because this target illuminance is not satisfied in this situation.

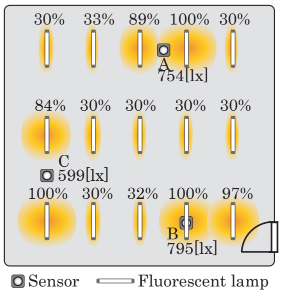


Figure 15. Before light 3 is failed

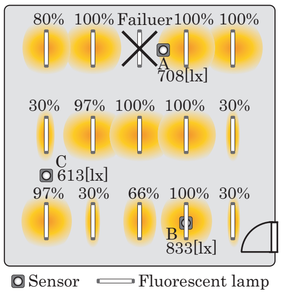


Figure 16. Steady state after light 3 is failed

Figs. 15 and 16 show the state before light 3 is failed and the steady state after failure occurred. In the steady state, the illuminance of each sensor becomes 708, 833 and 613[lx], therefore ANA/CC is thought to be effective when the light is failed. Comparing Figs. 15 and 16, we can see that the luminance of lights 1, 2, 5 ,7, 8 and 9 increased to compensate for the failure of light 3.

6 Conclusion

Intelligent lighting system which can contribute to energy saving, and which can provide the desired illumnance to desired locations based on the information from movable illumiance sensors was proposed. In this research, we proposed the new control method called ANA/CC. This algorithm calculates the correlation coefficient from the luminance and the illuminance to estimate the distance between the lights and the illuminace sensors. The valid tests were conducted using the proposed algorithm and the experimental intelligent lighting system. The result shows that the lights which are in near distance of the illuminance sensors gives appropriate luminance and the lights which does not affect any of the sensors have the minimum luminance. For these reasons, we confirm that ANA/CC is very effective control method for the intelligent lighting system. In this paper we only experimented with 15 lights, so in the future we will experiment on large-scale environment using ANA/CC.

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