Distributed Optimal Control of Lighting based on Stochastic Hill Climbing Method with Variable Neighborhood

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***Abstract*— In this research, a smart lighting system based on a new autonomous distributed control method was developed to control lighting using illuminance sensors. By using infrared ray communication, one illuminance sensor sends a luminance control directive to several lighting fixtures located nearby. The luminance is made to change randomly within a fixed range to optimize the illuminance using the stochastic hill climbing method. The result of operational experiments using illuminance sensors that were preset to the target illuminance showed that the brightness at specified locations approached the target illuminance that the illuminance sensors were set to. The electrical power consumed by the lighting system was also minimized. Moreover, in comparison with lighting driven autonomous distributed controls of smart lighting systems, better results were obtained, indicating that the method is an effective new distributed control method.**

I. INTRODUCTION

In recent years, the use of personal computers, the internet and electronic conferences in the office environment have become widespread, bringing about enhanced intellectual productivity. With the researches that have been conducted on the relationship between office environment and intellectual productivity up to present[1], it is not farfetched to presume that the office environment demanded of the future is an office able to provide an environment appropriate to the nature of work and to individual sensitivities. If this comes to pass, then not only will intellectual productivity improve. Creativity would likewise improve accompanied by the easing of stress at work.

The authors have been conducting research on office environment, paying special attention to the lighting environment. What is hoped for now with regards to the lighting environment is a lighting system that can provide individual brightness to a specific place that suits the nature of the work and individual sensitivities. Further, about 30 % of the electric power consumption of the entire building is used up in providing lighting to the office environment[2]. Hence, demand for a lighting system that, unlike current lighting system where all the lighting connected to the electrical lines are put on, conserves energy by putting the lights on only in places where lighting is needed. The authors have been conducting research and development studies on the so called smart lighting system[3], [4] as the next generation of lighting system that would turn this hope to reality. Smart lighting systems are, unlike computer controlled lighting systems[5], able to provide different illumination to individual places.

Smart lighting systems consist of lighting fixtures that can be controlled, movable illuminance sensors, microprocessors and an electric meter that are connected to a network. Lighting fixtures are each mounted with a microprocessor so that optimal lighting pattern for each lighting is achieved autonomously based on the information that flows through the network. In other words, smart lighting systems are lighting systems based on autonomous distributed control. Researches on smart lighting systems up to the present employed autonomous distributed control method that incorporates artificial intelligence on each lighting. However, when constructing a distribution control system, the question on what hardware should the artificial intelligence component of the system is a crucial research issue.

For that reason, this research incorporates the artificial intelligence component on the illuminance sensor, not on the lighting fixture in order to develop a new smart lighting system using autonomous distributed control where an illuminance sensor controls the lighting fixtures. This method of incorporating artificial intelligence component on the illuminance sensor is called“ illuminance sensor-driven smart lighting system ” to differentiate it from systems where the artificial intelligence component is incorporated on the lighting fixture itself and which is referred to as “ lighting fixture-driven smart lighting system. ”[3], [4]

II. ILLUMINANCE SENSOR-DRIVEN SMART LIGHTING SYSTEM

A. System Description

An illuminance sensor-driven smart lighting system is an autonomous distribution control system where the illuminance sensor mounted with a microprocessor is activated autonomously based on its own illuminance information and the electric power consumption data flowing in the network, controlling the lighting nearby. An illuminance sensor fitted with a microprocessor is called a smart illuminance sensor.

When all smart illuminance sensors control all the lighting, lighting that falls farther away beyond the smart illuminance sensor ’s influence are also controlled. This is not an efficient set-up. For that reason, it is necessary that the control range of the smart illuminance sensors should be restricted to the lighting nearby in order to improve control efficiency. This is done by using infrared ray communication technology to restrict this control range.

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Each lighting fixture has its own lighting ID, and the ID is transmitted by the infrared transmitter attached to the lighting fixture. The smart illuminance sensor receives the lighting ID's of nearby lighting fixtures.

Since infrared ray communication is directional, the range of infrared ray communication may be defined by controlling the angle of radiation. With this, a smart illuminance sensor communicates with the lighting falling within the range of the infrared ray communication and can retrieve lighting ID, thus, enabling the smart illuminance sensor to recognize whether the lighting falls nearby or farther away. Consequently, the control range of a smart illuminance sensor may be set to lighting whose lighting ID could be retrieved. In this way, the control range of a smart illuminance sensor may be restricted in order to increase its control efficiency.

In addition, one smart illuminance sensor can control and synchronize lighting at the same time. By exploiting this capability, the sensor is able to change the luminance of lighting within its range of control by a fixed amount according to a preset order. This allows measurement of the influence exerted by the smart illuminance sensor on each lighting, called measurement of influence factor. This further allows each lighting to be ranked according to the degree of influence which enables control of lighting based on the ranking that was established.

Fig. 1 illustrates the construction of an illuminance sensor-driven smart lighting system.

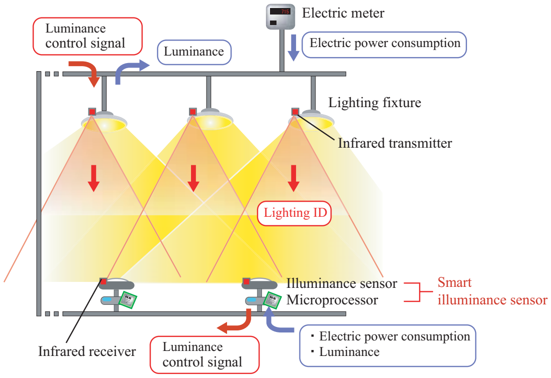


Fig. 1. The construction of an illuminance sensor-driven smart lighting system

B. Control Algorithm

The control algorithm is an improved algorithm based on stochastic hill climbing (SHC). The flowchart for this algorithm is shown in Fig. 2.

The flow of control is shown below.

1) Target illuminance is set on the smart illuminance sensor.
2) Each lighting is lit up with an initial luminance.
3) The control range of each smart illuminance sensor is established using infrared ray communication.
4) Smart illuminance sensor measures the influence factor described in Section II-A and ranks each lighting accordingly.

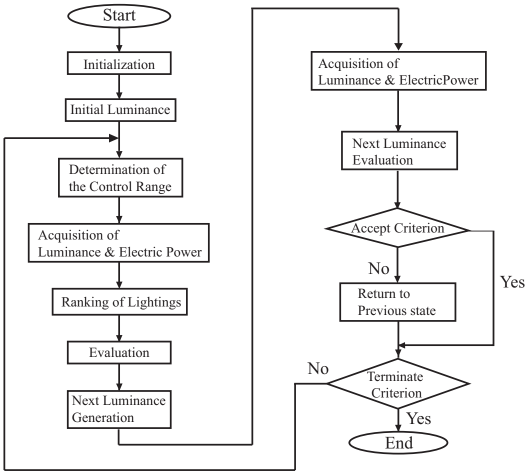


Fig. 2. Control algorithm

5) Smart illuminance sensor retrieves information on the illuminance of the lighting within the controlled range as well as the whole electrical power consumed by the lighting through the network.
6) Based on the information retrieved and its own illuminance information (current illuminance, target illuminance), the value of the objective function as explained in the following section is calculated.
7) Appropriate range of luminance change for each lighting is established based on the ranking derived from the measurement of influence factor and illuminance information. The range of luminance change is the maximum value of the difference between the current luminance and the luminance for the next condition.
8) Luminance for the next condition is generated at random within the range of luminance change.
9) Each smart illuminance sensor sends the luminance determined for the next lighting condition for each lighting within the control range to cause the luminance for each lighting to change.
10) Calculates the value of the objective function for the next condition.
11) If the value of the objective function improves, the luminance is settled. Returns to Step 3. If the value of the objective function worsens, the luminance change is cancelled. Returns to Step 3.

When the steps outlined above are performed, it is expected that the illuminance will converge to the target illuminance. The reason for the return to Step 3 done at Step 11 is to enable the illuminance sensor to adapt to changes in environment such as movement of the illuminance sensor and infiltration of outside rays within the operational duration of Steps 4 $\sim$ 11.

Each smart illuminance sensor sends the luminance control command to the nearby lighting fixtures asynchronously. This command is received by the lighting fixtures using Ethernet LAN. When a lighting fixture receives several control commands asynchronously from several smart illuminance sensors, the lighting fixture adopts the average value of those luminance values.

C. Objective Function

The smart lighting systems aims to draw the current illuminance of each illuminance sensor close to the target illuminance that had been set and to minimize the amount of electric power consumed. When expressed in a formula, Equation (1) results.

$$\begin{aligned} f_i &= P + w \cdot g_i \\ g_i &= \begin{cases} 0 & (Lc_i - Lt_i) \geq 0 \\ (Lc_i - Lt_i)^2 & (Lc_i - Lt_i) < 0 \end{cases} \end{aligned} \tag{1}$$

$$i : Illuminance\ sensor$$
$$P : Electric\ power,\ w : Weight$$
$$Lc : Current\ illuminance,\ Lt : Target\ illuminance$$

The luminance of each lighting is set as design variable with the aim of minimizing the objective function f_i for the illuminance sensor i. f_i consists of g_i, the difference in illuminance between Lc_i, the current illuminance and Lt_i, the target illuminance, and P, the electrical power consumed. g_i is added only when its value is negative. In other words, when the current illuminance is smaller than the target illuminance, g_i becomes larger and the objective function increases. The data for electric power consumption P is be obtained through an electric meter connected to the network. This objective function may be assigned to each smart illuminance sensor. The entire system is optimized when each smart illuminance sensor minimizes each objective function.

D. Range of Luminance Change (Neighborhood)

Fig. 3 shows seven ranges of luminance change used in the random dimming and brightening of the lighting system to generate the luminance for the next condition. Seven ranges of luminance change is required from the selection standards shown in Table. I. These ranges of luminance change are the range of change for the design variables, in other words, the neighborhood, used in the stochastic hill climbing method, referred to as neighborhood hereinafter. The values appearing in Fig. 3 represents the relative ratios when maximum luminance is 100 %. These numerical values are values that have been fine-tuned during the preliminary experiment.

A represents the neighborhood where importance is given to rapid decrease in luminance, B the neighborhood where importance is given to gradual decrease in luminance as compared with A. C, D and E are the neighborhoods where the luminance is adjusted. C represents a neighborhood where the luminance tends to decrease while E represents a neighborhood where the luminance tends to increase. F is a neighborhood where importance is given to gradual increase in the luminance while G is a neighborhood where importance is given to rapid increase in the luminance. The illuminance sensor allocates one neighborhood that is appropriate to the lighting from within the seven neighborhoods shown in Fig. 3 based on the measurement of influence factor ranking and illuminance information in accordance with the selection standards shown in Table. I and generates the luminance for the next condition using random number within the range.

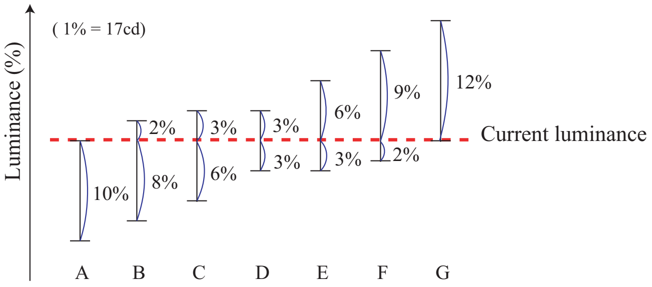


Fig. 3. Seven neighborhoods

TABLE I
THE SELECTION STANDARDS OF NEIGHBORHOOD

Ranking / Current illuminance	1st	2nd	3rd	4th
Larger than target illuminance	C	B	B	A
Convergence state at target illuminance	E	D	C	C
Smaller than target illuminance	G	F	E	D

III. OPERATIONAL EXPERIMENT

A. Outline of Experiment

To determine the effectiveness of illuminance sensor-driven smart lighting system (referred hereafter as Sensor-SLS), operational experiments under two experimental environments were examined to verify whether the target illuminance could be realized and sustained using low power supply. In addition, comparison was made with the lighting fixture-driven smart lighting system (referred to hereafter as Lighting-SLS) with proven effectiveness. Fig. 4 shows the experimental environment. The figure shows the plain view of the experiment room, which has a floor area of about 60 m^2, and the location of the fluorescent lamps and the illuminance sensor inside . The circle indicated in the figure shows the range of infrared ray communication, that is, the range of control of the smart illuminance sensor. The parameter settings used in the experiment are summarized in Table. II.

Experiment 1 : With no change in the environment
The target illuminance intensities of the illuminance sensors A, B and C are 750, 700 and 800 lx respectively.

Experiment 2 : With the illuminance sensor moved
The illuminance sensor A is moved from the steady state condition of Experiment 1 to the center of Lighting 6, 7, 11 and 12.

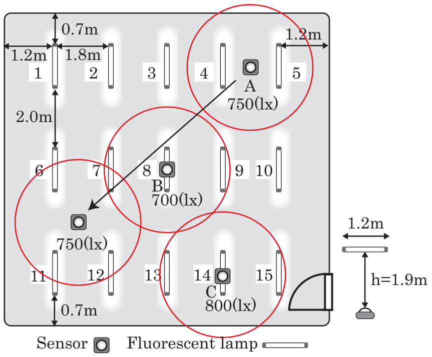
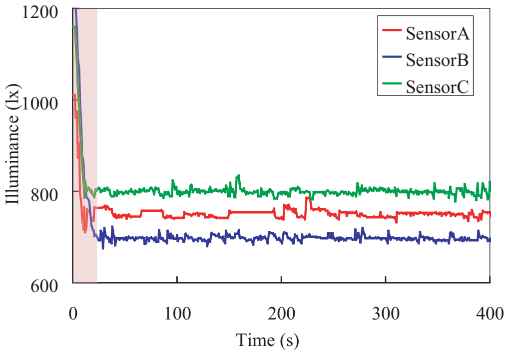


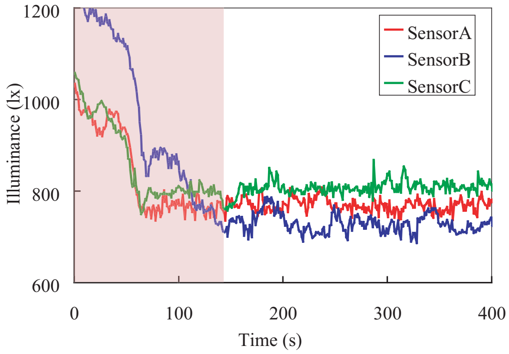
Fig. 4. Experimental environment

TABLE II
PARAMETER SETTINGS

Number of fluorescent lamps	15
Number of illuminance sensors	3
Target illuminance (lx)	750, 700, 800
Maximum luminance (cd)	1700
Minimum luminance (cd)	510
Initial luminance (cd)	1700



(a) Sensor-SLS



(b) Lighting-SLS

Fig. 5. Illuminance history (Experiment 1)

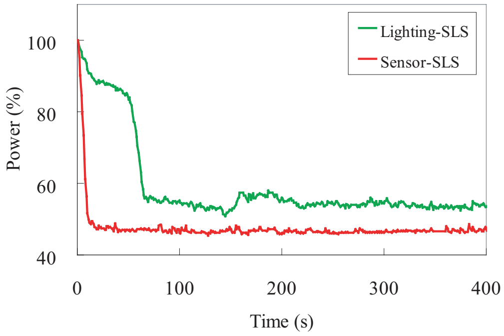


Fig. 6. Electrical power history

B. Experimental Results

1) Experiment 1: The experiments were conducted 10 times, and almost the same results were obtained. Therefore, the typical results are shown here. Fig. 5 summarizes the illuminance history of the smart illuminance sensors. The horizontal axis of the figure represents time while the vertical axis represents illuminance. Fig. 5 (a) shows the results for Sensor-SLS, Fig. 5 (b) the results for Lighting-SLS. Fig. 6 shows the electrical power consumption for both Sensor-SLS and Lighting-SLS. The horizontal axis represents time while the vertical axis represents the ratio of electrical consumption with the 100 % electrical consumption registered when all the lighting fixtures are lit up at maximum luminance.

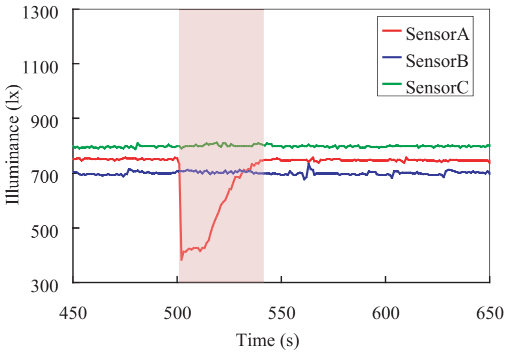
Fig. 5 (a) shows that the illuminance at the start of the experiment for Sensor-SLS decreased. After about 20 seconds, illuminance sensors A, B and C registered illuminance of 735, 715 and 805 lx, which almost converged to the target illuminance. In comparison, Fig. 5 (b) shows that for Lighting-SLS all the illuminance converged after 120 seconds. This indicates that Sensor-SLS converges to the target illuminance faster. Further, it is seen that Sensor-SLS is more stable after converging to the target illuminance.

Next, Fig. 6 shows that, similar to the illuminance history, the energy consumption of Sensor-SLS decreases faster. Further, the reduction in energy consumption brought about by the use of Sensor-SLS is greater by about 10 % than the reduction brought about by the use of Lighting-SLS.

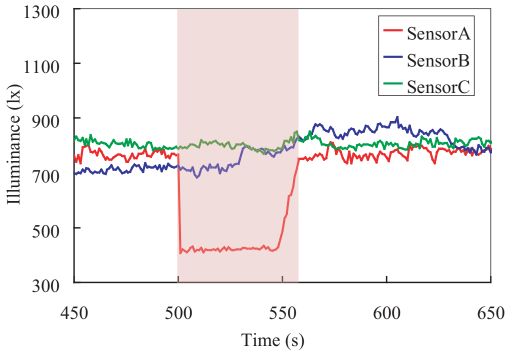
2) Experiment 2: Fig. 7 shows the illuminance history for all smart illuminance sensors. Fig. 7 (a) shows the results of the experiment using Sensor-SLS, Fig. 7 (b) the experimental results using Lighting-SLS.

Fig. 7 (a) shows that the illuminance of illuminance sensor A decreases to a large extent from the target illuminance immediately after moving illuminance sensor A (500 seconds). However, after 40 seconds the illuminance returns to the target illuminance. In like manner, Fig. 7 (b) shows that the illuminance of illuminance sensor A decreases to a large extent from the target illuminance immediately after moving illuminance sensor A and that recovery of the illuminance up to the target illuminance required 60 seconds. It is obvious that Sensor-SLS satisfies the target illuminance faster even after the illuminance sensor is moved. In this instance, it can be seen that in Lighting-SLS, the illuminance of illuminance sensor B that has not moved is also affected.

Fig. 8 shows the steady state conditions of luminance in Sensor-SLS before and after the moving of sensor A.

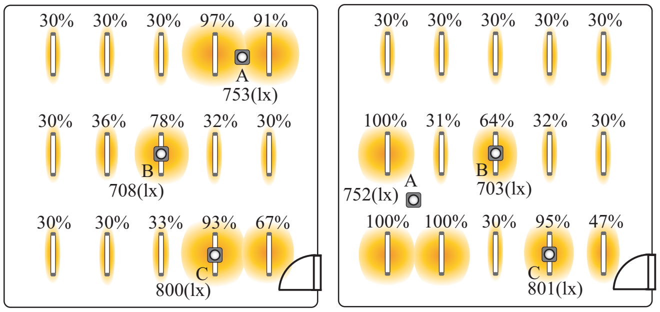


(a) Sensor-SLS



(b) Lighting-SLS

Fig. 7. Illuminance history (Experiment 2)



(a)Illuminance sensor before being moved

(b)Illuminance sensor after being moved

Fig. 8. Steady state of luminance

Fig. 8 shows that the final illuminance of each illuminance sensor registered 752, 703 and 801 lx, indicating that the illuminances were converging to the target illuminance. Comparing Fig. 8 (a) and Fig. 8 (b), it is confirmed that the luminance of the lighting located at the nearby place where illuminance sensor A was moved to increased and some lighting which shown brightly before the transfer decreased to the minimum luminance. From these observations, it is clear that convergence to the target illuminance even under changing environment and reduction in electric power consumption are realizable.

IV. CONCLUSION

In this experiment, an illuminance sensor-driven smart lighting system was constructed where a microprocessor was mounted on an illuminance sensor to develop a smart lighting system based on a new autonomous distributed control method. The effectiveness of the new system was evaluated in an operational experiment. The results of the operational experiments showed that the system responds to changes in the environment to converge quickly to the target illuminance with reduced electrical power consumption. Further, the new system showed better results when compared with lighting fixture-driven smart lighting systems that have been in use until now. From these, it can be concluded that illuminance sensor-driven control is an effective new autonomous distributed control method.

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