Intelligent Lighting System with an Additional Energy-Saving Mechanism

Mitsunori Miki
Department of Science and Engineering
Doshisha University
Kyoto, Japan
mmiki@mail.doshisha.ac.jp

Masashi Nagano
Graduate School of Engineering
Doshisha University
Kyoto, Japan
mnagano@mikilab.doshisha.ac.jp

Masato Yoshimi
Department of Life and Medical Sciences
Doshisha University
Kyoto, Japan
myoshimi@mail.doshisha.ac.jp

Hiroyuki Yonemoto
Graduate School of Engineering
Doshisha University
Kyoto, Japan
hyonemoto@mikilab.doshisha.ac.jp

Kenta Yoshida
Graduate School of Engineering
Doshisha University
Kyoto, Japan
kyoshida@mikilab.doshisha.ac.jp

***Abstract*—Intelligent lighting systems have been able to realize a minimum electrical power consumption for a given arbitrary illumination in an arbitrary location. By randomly increasing and decreasing the brightness of each lamp, the lighting intensity is controlled and the required parameters for this control are then learned. For this reason, lamps need to be lit above a certain brightness level, and when the user is away from their seat, for example, even in a place where illumination is not needed, the lights are not turned off. These intelligent lighting systems have achieved high energy savings using different lighting for each individual, but, from the viewpoint of additional energy saving, it would be desirable for a mechanism which could also turn out lights. Therefore, in this study, we propose a mechanism to turn out any unnecessary lights appropriately as the users are away from their seats. To verify the effectiveness of the proposed system, as a performance test, we set up an experimental system using 10 dimmable fluorescent lamps and 10 illuminance sensors to compare the energy saving with that of a conventional intelligent lighting system. It was confirmed that the proposed system was also able to realize an illuminance convergence capability similar to conventional systems, while additional high energy saving was also possible.**

***Index Terms*—energy saving, office environment, lighting control, intelligent, optimization**

I. INTRODUCTION

The drastic reduction in the amount of energy used in Japan is an issue of pressing urgency. In particular, the energy consumed in buildings used for business increases yearly, and so energy saving in this sector will lead to significant energy reductions for the whole country. Approximately 20% of the total power costs in office buildings is taken up by lighting[1], and so finding energy-saving measures for lighting is an important challenge.

The authors are currently working on the research and development of lighting systems referred to as intelligent lighting systems[2]in order to resolve this issue. Intelligent lighting system is configured using multiple dimmable lighting fixtures incorporating microprocessors, multiple illuminance sensors and also a power meter, all connected in a network. A given arbitrary brightness in some arbitrary location can be provided autonomously with an optimum lighting spattern for each of the lamps, based on both the illuminance information and information about the electrical power consumption which is passed through the network. Following verification of intelligent lighting system in the laboratory in April 2009, we were able to verify its effectiveness when we carried out a test demonstration in the urban planning project office of Mitsubishi Estate Co., Ltd. in the Otemachi building in Toyko[3].

In intelligent lighting system, it is possible to realize a different illuminance for each individual, with the result that the average value of the illuminance achieved is greatly reduced, along with the accompanying large reduction in electrical power consumption. Thus, the intelligent lighting system is important as a solution for energy saving in office buildings.

The positional relationship of the lamps and illuminance sensors in intelligent lighting system is sequentially varied randomly within a range in which the brightness of the lamps is not humanly perceptible. This is done such that it is possible to carry out optimum lighting control through a thorough understanding of the positional relationship between the lamps and illuminance sensors, as well as the dynamic changes in the environment and the natural light from outside.

This is why, if certain lamps are turned off, the dynamic understanding of the effect of the lamps on the illuminance sensors would no longer be possible. Therefore, even in places where light is not needed when an office worker is not there, lamps should be still turned on with a minimum brightness, the concept of actually switching off lights in the conventional sense has not been addressed so far.

This was recognized to be true from the viewpoint of office safety, prior the Great East Japan Earthquake of March, 2011.

However, many office workers had left their seats after the earthquake, so even though only minimum lighting was provided in places where lighting is not necessarily required, the lights were left on and this is considered to be a real drawback in terms of increasing energy savings.

With the lights-out lighting control that utilizes eaway from deskf sensors, which is currently being used in many offices, control for turning off all of the lights has been used for the first time in a situation in which everybody is absent from their seats within a given area (for example, an office space of about 20 people).

On the other hand, in intelligent lighting system for performing optimum lighting control by sensing the positional relationship between the lamps and illuminance sensors, a more refined lights-out control for each light would be possible if such a lights-out control could be implemented.

In this respect, in this study we propose a control approach which aims to enhance additional energy saving by enabling a mechanism to turn off lights which has, as yet, not been implemented in intelligent lighting systems of the past. This method can only be used with the proviso that the sensor positions are fixed and cannot be used when the positions of the sensors can change.

II. INTELLIGENT LIGHTING SYSTEM

A. *Overview of intelligent lighting system*

intelligent lighting system is a lighting control system which provides an appropriate brightness as expected by a user in an arbitrary location. It consists of multiple dimmable lighting devices and multiple illuminance sensors, together with a power meter, connected to a single network. The configuration of intelligent lighting system is shown in Fig.1.

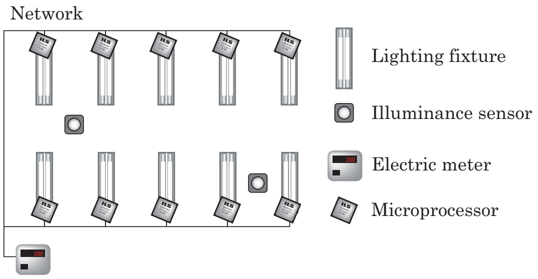


Fig. 1. The construction of a lighting fixture-driven smart lighting system

An illuminance sensor is provided for each user, and the brightness in front of the user is measured by the sensor. Also, the target illuminance may be entered by the user through an interface of intelligent lighting system. In the control device installed for each lighting device, illuminance information is collected from each illuminance sensor together with information about the power consumption from the power meter. Based on this data, the control device can then adjust the lamp brightness according to an optimization technique to achieve the brightness requested by the user while also striving to keep the power consumption to a minimum. Although there are no limitations on either the number of lamps or the number of illuminance sensors in intelligent lighting system, if the difference in the target illuminances of adjacent illuminance sensors is very large, for example, and the target illuminances cannot physically be achieved, then, of course, the targets cannot be adequately met. For normal office lighting fixture spacing (a pitch of 1800mm), or normal office desk spacing (a pitch of 1200mm), the maximum achievable difference in illluminance between illuminance sensors placed atop adjacent office desks is about 200 lx.

B. *Objective function*

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.

$$
\begin{aligned}
f_i &= P + w \sum_{j=1}^{n} g_{ij} \quad i = 1, 2, 3, ..., m && (1) \\
g_{ij} &= \begin{cases} 0 & (Lc_j - Lt_j) \geq 0 \\ R_{ij}(Lc_j - Lt_j)^2 & (Lc_j - Lt_j) < 0 \end{cases} \\
R_{ij} &= \begin{cases} r_{ij} & r_{ij} \geq Threshold \\ 0 & r_{ij} < Threshold \end{cases}
\end{aligned}
$$

f:Objective function, i:light number, m:Number of light
n:Number of illuminance sensors, w:Weighting factor
P:Amount of consumed electrical power
Lc:Current illuminance, Lt:Target illuminance
r:Correlation coefficient, $Threshold$:Threshold value

Making the brightness for each lamp the design variable, we aim to minimize the f in Eq.1. f_i 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_i 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.

C. *Lighting control algorithm*

The authors have suggested the Adaptive Neighborhood Algorithm using Correlation Coefficient (ANA/CC) [4] as an illuminance control algorithm which is based on the Stochastic

Hill Climbing (SHC) method. The flow of this algorithm is explained below.

1) Illuminate with the initial lighting intensity
2) Collect the sensor data for each illuminance sensor (the sensor ID, current illuminance, and target illuminance), and the amount of consumed electrical power for the power meter, and then calculate the value of the objective function using this data.
3) Determine the appropriate neighborhood based on the sensor information and the correlation coefficient (The neighborhood is the range used to generate the next light intensity. It is described in detail in section II-D.j
4) Randomly generate the next light intensity within the range determined in step 3, and illuminate the lamp with that light intensity.
5) Collect sensor data from each sensor and the amount of power consumption from power meter again, and use this data to calculate the value of the objective function when lighting with the next light intensity.
6) Calculate the correlation coefficient using the variation in the light intensity of the lamp and the variation in the illuminance of the illuminance sensor.
7) If the value of the objective function has improved, determine the light intensity and return to step 2.
8) If the value of the objective function in step 5 has deteriorated, illuminate again with the same light intensity as before and return to step 2.

From the above operations, the rough positional relationship between the lamps and the illuminance sensors is acquired, and in satisfying the target illuminance, it rapidly converges to an electrical power saving state. Also, as the correlation coefficient calculated in step 6 is required for lighting control, even for places where no light is necessary when a worker has left their seat, the lamp is lit more than the minimum luminance without being turned off.

D. Design of the neighborhood

In intelligent lighting system algorithm, three types of neighborhoods, are used to generate the light intensity in the next state as shown in Fig. 2. If an increase in light intensity is needed for a given lamp, the neighborhood biased for brightening is used, whereas when a decrease in light intensity is needed, the neighborhood biased for dimming is used. As shown in Fig. 2, three types of neighborhoods are used, (A) biased for dimming, (B) neutral, and (C) biased for brightening. These three types of neighborhoods are adaptively selected using the correlation coefficient and the illuminance value for each illuminance sensor. The numbers shown in Fig. 2 give variations of light intensity where the maximum light intensity for lighting is taken as 100%.

III. ENERGY SAVING IMPROVEMENTS WITH A LIGHTS-OUT CONTROL IN INTELLIGENT LIGHTING SYSTEMS

A. The need for a lights-out control

Since intelligent lighting systems provide a brightness appropriate for each user by using an optimization algorithm, the amount of electrical power consumed is greatly reduced in comparison with conventional lighting systems which provide just a uniform lighting, and so the energy saving is high [5].

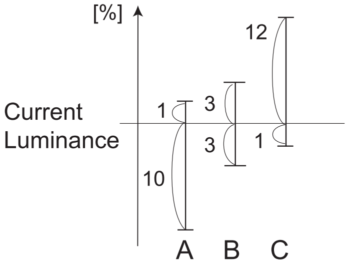


Fig. 2. Three types of the neighborhood

The energy saving is heavily dependent on the dimming range. For example, the energy-saving effect is increased using lighting fixtures which are continuously dimmable to 25% of the light intensity rather than to 50%. This is due to the fact that it is possible to decrease the illumination to handle such cases as people who prefer low lighting, and those at work who are away from their desks or have left the office.

In current intelligent lighting systems, when using fluorescent lighting fixtures, the dimming lower limit is generally around 20% because of problems with the fixture, which means that many lighting fixtures are at 20% lighting luminosity even when lots of people are away from their desks, and the energy saving is then restricted to that value. To get a higher energy saving than this, unnecessary lighting fixtures are turned off instead of lighting with the minimum lighting luminosity of 20%.

However, these intelligent lighting systems do not turn off lights even in locations where lighting is not necessary as the users are either away from their seats or have left for the day. This is because the light intensity of each lamp is constantly being randomly increased and decreased within a range which is not perceptible to humans, and using the correlation coefficient for that variation in light intensity and the variation in illuminance measured at each illuminance sensor, the lighting is controlled after establishing the approximate positional relationship between the lamps and the illuminance sensors. Turning off the lights makes it impossible to dynamically obtain the correlation coefficient, and optimum control of the lighting cannot be done. If all the users had left the office and there was no possibility of changes in the environment, it was obviously acceptable to simply turn off lights for those which have a power switch installed in the wall. However, when there was a possibility of dynamic changes with regard to the users (the illuminance sensors), it was necessary to have the lights turned on continuously at or above a minimum brightness level.

B. A mechanism to control the switching of lights on and off

The rough positional understanding of the lamps and the illuminance sensors, from the random changes in the light intensity of the lamps and the random changes in the illuminance measured at the illuminance sensors, cannot be performed if lights-out control is implemented. We therefore have to establish the positional relationship of the lamps and the illuminance sensors in advance. Illuminance sensors found to have a close positional relationship are registered in a database as affected illuminance sensors, and this information is used in controlling the turning on and off of the lights.

As it is usual to install illuminance sensors at each desk in an office environment, it is therefore possible to acquire this positional relationship. The positional relationship is acquired based on the illuminance values at each of the illuminance sensors when these values are measured in advance as the lights are turned on one at a time.

The lights-out control is performed using the following concept. Namely, if the target illuminance for all the illuminance sensors affected by a lamp is not required, the lamp is turned off. The flowchart for the lighting control algorithm is shown in Fig. 3, incorporating a control for switching the lights on and off, and the flow of this algorithm is explained below. The portion enclosed by the dashed line in Fig. 3 shows the control for turning on and off the lights. the other side shows intelligent lighting system control for the configuration which does not include the control for turning on and off the lights.

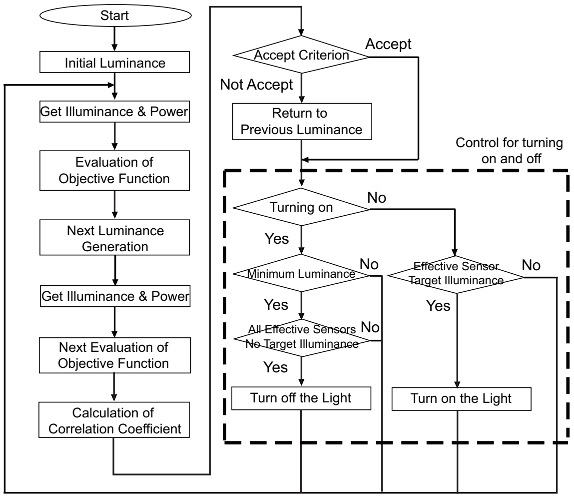


Fig. 3. Control algorithm

1) Lighting is controlled as outlined in section II-C.
2) A lamp has a minimum illuminance, and if the target illuminance for all the illuminance sensors affected is not required, it is turned off. In this case, the IDs are recorded of the illuminance sensors which are affected by this lamp directly before it is turned off.
3) A lamp has been turned off, but if a target illuminance which is not 0 lx is required for the illuminance sensors whose IDs were recorded when the lamp was turned off, it is turned on with the minimum luminance.

Carrying out the control in this way makes it possible to converge to the target illuminance and adaptively control the turning on and off of the lights.

IV. VALIDITY ASSESSMENT OF THE LIGHTS-OUT CONTROL IN INTELLIGENT LIGHTING SYSTEMS

A. *Outline of the experiment*

In order to verify the effectiveness of the proposed system, we compared the energy saving capability of a conventional intelligent lighting system and the proposed system. The experiment was carried out by first setting up a temporary ceiling in a student room at the university, and putting together an environment as shown in Fig. 4(A) and (B) using 10 neutral white illumination lamps and 10 illuminance sensors. Fig. 4(B) illustrates the positional relationship between the fluorescent lamps and the illuminance sensors, and shows the fluorescent lamp number next to the lamps in the figure, and also letters next to the illuminance sensors as both sensor identifiers and test subject names. The dimming range for the fluorescent lamps used in this experiment was from 20% to 100%. The parameters used in the experiment are shown in Table I.

The experiment was carried out for intelligent lighting system and subsequently with the proposed system based on the target illuminances that were obtained and the schedule for the presence or absence of test subjects in their seats, and a comparison made between the two systems. Also, to eliminate the effect of external light, the experiments were conducted at night. The target illuminance settings were 600 lx for subjects A, G and H, 500 lx for subjects B, C, F, and I, and 400 lx for subject J, while the subjects D and E were away from their seats all day.

The schedule indicating the subjectsf presence or absence is as shown in Fig. 5. Fig. 5 has time along the horizontal axis and the seat occupancy along the vertical axis. Each user of intelligent lighting system presses the eaway from seatf button on the individual user interface when they are absent. That userfs target illuminance is thus 0 lx.

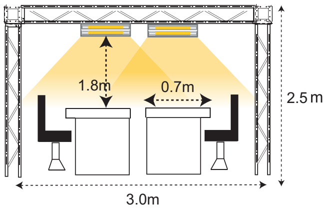
From this data, the experiments were carried out using a real system which included the lights-out control, and also a system which did not. That is, after setting the target illuminance for 10 people and the schedule of their presence and absence, we then demonstrated how the systems behaved.

TABLE I
PARAMETERS

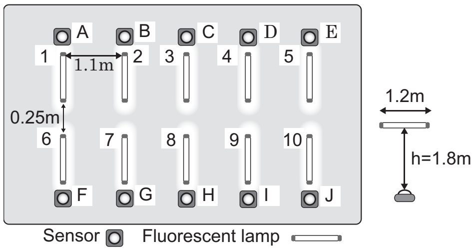
Number of fluorescent lamps	10
Number of illuminance sensors	10
Weight	1.0
Target illuminance [lx]	0, 400, 500, 600
Maximum luminance [cd]	1050
Minimum luminance [cd]	210
Initial luminance [cd]	1050

B. *Experimental results and discussion*

1) Verification of illuminance convergence: Next, we verified the illuminance convergence for the proposed system. The history of the illuminance and the target illuminance for Sensor H in both the conventional and the proposed systems



(A) Side view



(B) Top view

Fig. 4. Experiment Environment

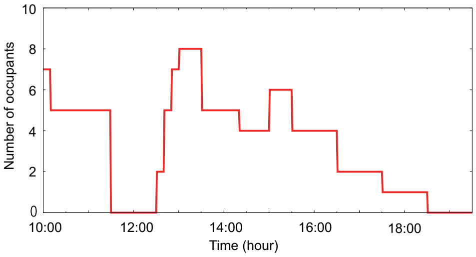


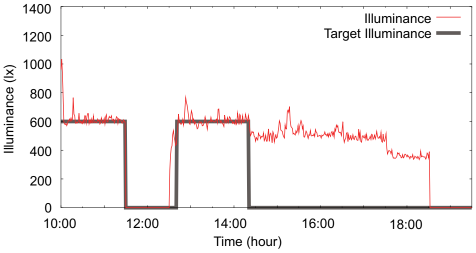
Fig. 5. Number of seat occupancy

is shown in Fig. 6. Fig. 6 has time along the horizontal axis and illuminance along the vertical axis.

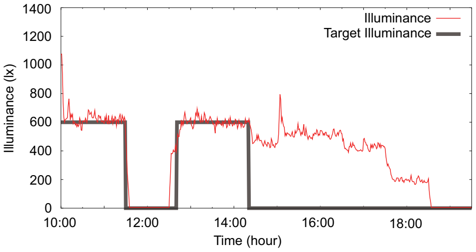
According to Fig. 6, we find that in the time period when the user is at their desk and a target illuminance has been set of 600 lx, the error between the target illuminance and the current illuminance is small for both the conventional and the proposed systems, and also the target is met. Further, for the target illuminance of 600 lx over the time zone from 12:40 until 14:20, Fig. 7 shows the luminance (%) for each lamp, as well as the illuminance for the sensors. The target illuminance is shown in parentheses in the figure, and the current illuminance as the value above that.

According to Fig. 7, in contrast to the conventional system where no lamps were turned off, the lamps which did not affect Sensor H in the proposed system, that is, the three lamps, lamp 4, lamp 5 and lamp 10, are turned off. In other words, we can conclude that the lights-out control has performed effectively according to the users being absent from their seats.

2) Verification of energy saving capability: We verified the energy saving capability for the proposed system. A history of the electrical power consumption for both the proposed and the conventional systems is shown in Fig. 8. Fig. 8 has time along the horizontal axis and the electrical power consumption along the vertical axis as a percentage. Since it has been stipulated that a desktop illuminance level of 750 lx must be met in an office , the electrical power consumption for the lighting conditions to achieve that is taken as 100%. The lighting conditions to satisfy a desktop luminance of 750 lx was determined through preliminary experiments. In the conventional system, the power consumption was 0% after 18.30. This was because all the users had left their desks, and the lights had been turned off using the power switches installed in the wall. For the periods in Fig. 8 from 13:30 to 15:00 and again, from 16:30 to 18:30, a large reduction in electrical power consumption is seen for the proposed system compared to the conventional system. On the other hand, the power consumption for both systems from 15:00 to 16:00 was identical. This was because, for the proposed system, lamps

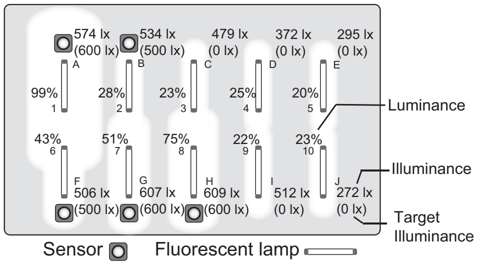


(a) Conventional Method(ANA/CC)

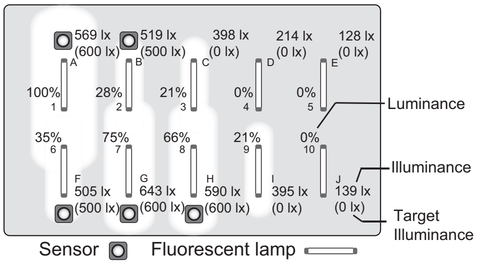


(b) ANA/CC with an Additional Energy-Saving Mechanism

Fig. 6. History of illuminance(Sensor H)



(a) Conventional Method(ANA/CC)



(b) ANA/CC with Additional Energy-Saving Mechanism

Fig. 7. Luminance(Effect of the additional energy-saving mechanism)

were not turned off for the given pattern of test subjects away from their seats. The difference in energy saving due to the pattern of absence is discussed in section 4.2.3. Compared to the conventional intelligent lighting system, a reduction of about 13% in the total power consumption was achieved during the day. With these results in mind, we can reasonably state that additional energy saving has been realized by means of this lights-out mechanism, and the proposed system is effective.

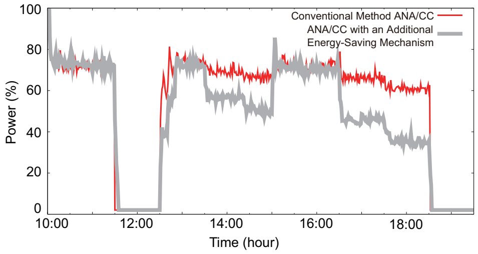
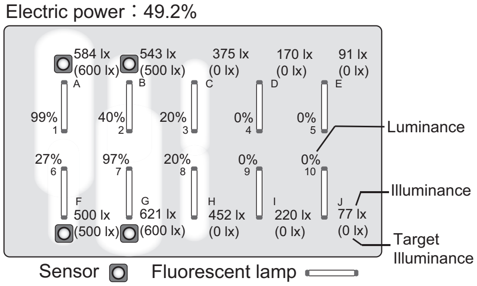
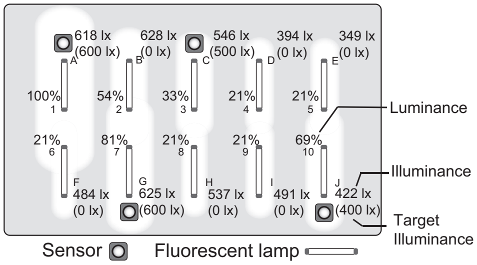


Fig. 8. History of electric power

3) Verification of the energy saving capability due to the seat absence pattern: We verified the energy saving capability with the proposed system which was associated with the pattern of absence of test subjects from their seats. Fig. 9 shows the luminance (%) for each lamp and the illuminance for each illuminance sensor with a user seating occupancy of 40%, as well as the power consumption at that time. In Fig. 9(a), test subjects C, D, E, H, I and J were away from their seats, and in (b), test subjects B, D, E, F, H and I were away from their seats.



(a) test subjects C,D,E,H,I,and J were away



(b) test subjects B,D,E,F,H,and I were away

Fig. 9. Luminance(Effect of the location of seat occupancy)

According to Fig. 9, we can see that for both patterns, the target illuminance for each test subject has been achieved. While this was true, there were 4 lamps extinguished in Fig.9 (a), lamp 4, lamp 5, lamp 9 and lamp 10, whereas there were no extinguished lamps in Fig.9(b). This difference was because in Fig. 9(a), the absent users were distributed concentrated together, whereas in Fig.9(b), they were distributed in a dispersed fashion. The users in the office being spread out implies that the affected lamps were also spread out, and so there were no extinguished lamps. Because of this fact, the power consumption for the pattern of absence in Fig. 9(a) was 49.2%, but was 72.6% for the pattern in Fig. 9(b). A difference of about 23% was found in the power consumption due to the pattern of absence from seats even for cases where the seating occupancy was the same.

V. CONCLUSION

In this study, for a given arbitrary brightness and location, in order to further enhance the energy savings of intelligent lighting systems which have a lower limit for power consumption, we proposed a novel control technique which can also turn off lights, thereby improving the conventional method, which assumes the minimum luminance for the fluorescent lamps set by their dimming range. The lighting intensity for lamps in intelligent lighting system is randomly increased and decreased constantly, and by this means, while dynamically learning the required control parameters, control of the lighting is thus performed. For this reason, it has always been absolutely essential that lamps are lit with more than a minimum luminance, and extinguishing lamps was not done. However, to increase the energy saving capability of intelligent lighting systems even further, in an environment with fixed illuminance sensors, and by recording the illuminance sensors which are affected by each lamp, it was possible to turn off lights and turn them back on again. We confirmed that it was possible to achieve high energy savings with the novel control technique which includes turning off lights.

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