Evaluation of Illuminance Provided by the Intelligent Lighting System in Actual Office

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***Abstract*—In our laboratory, lighting control system targeting office environment called Intelligent Lighting System has been proposed. Intelligent Lighting system is not the existing lighting system that provides uniform illuminance, but it can individually provide different illuminance depending on a worker's work content and preference. Presently, prototype Intelligent Lighting Systems are introduced to some office buildings to conduct demonstration experiment for commercialization. Illuminance condition of areas where illuminance sensors were installed is achieved in the demonstration experiment, and it was confirmed that each worker can work comfortably with illuminance they selected. However, illuminance of the entire room provided by Intelligent Lighting System had not been reviewed. Evaluation by illuminance distribution is also important for Intellectual Lighting System since it provides different illuminance to workers. Therefore, this study mentions evaluation of illuminance provided by Intelligent Lighting System in actual office environment by using the system which can measure illuminance distribution.**

***Index Terms*—Optimization, Lighting Control, Illuminance Distribution, Office Environment**

I. Introduction

As electronic control technologies and information processing technologies develop in recent years, intelligence has been incorporated in various devices and systems including electric appliances and automobiles, where the system autonomously controls its movement and management depending on a user or environment and burdens to people are reduced. The intelligent system has the ability to take proper actions by thinking, understanding and making judgments based on its own knowledge obtained from information using a sensor, etc. With the intelligent system, autonomous movements in response to the surrounding environment are possible, user satisfaction is improved, and it is possible to flexibly respond to various environmental changes[1].

On the other hand, improvement of office workers' intelligent productivity, creativity and comfortableness in offices has been focused on in recent years[2], [3]. And it is clarified in the study by Boyce, etc. that to provide illuminance most suitable for execution of work for each individual is effective from the viewpoint of improving the lighting environment[4]. To provide brightness most suitable for execution of work for each individual is easily realized with task and ambient lighting. However, ceiling lighting fixtures which provide even brightness on a floor are common in office buildings in Japan, and it is not easy to adopt task and ambient lighting. Therefore, the lighting control system to provide brightness most suitable for each office worker is necessary by using ceiling lighting fixtures.

Based on the above viewpoints, our laboratory has been conducting research on intelligent lighting system which provides illuminance appropriate for office workers' needs. The intelligent lighting system consists of lighting fixtures equipped with a microprocessor, illuminance sensors and an energy meter connected to the network. Intelligent lighting system allows each worker to set the ideal illuminance on his/her own illuminance sensor. The system can achieve a lighting pattern with the smallest electric power and at the same time satisfy the set illuminance value by using optimization method. A basic experiment revealed that intelligent lighting system presently is able to satisfy a user's ideal illuminance and achieve high rate of energy saving. Verification experiments have been conducted for actual use in offices[5].

The intelligent lighting system uses an illuminance sensor installed at each worker's desk for controlling. Therefore, the illuminance condition is satisfied in an area where an illuminance sensor is installed, and each worker can work comfortably under the brightness s/he selected. However, illuminance had not been examined in areas around where illuminance sensors are installed and where the sensors are not installed. Therefore, our laboratory has developed illuminance distribution measurement system in order to evaluate such illuminance[7].

This study mentions evaluation result of illuminance provided by Intelligent Lighting System in actual office environment by using illuminance distribution measurement system. Evaluation items are; illuminance of areas around where illuminance sensors are installed (work area) and of areas where illuminance sensors are not installed (allies, etc.).

CIE recommends the balance rate (ratio of minimum illuminance against average illuminance) in a work area shall be 0.7 or more, and 0.5 or more around a work area for illuminance evaluation in this work area[8]. Therefore, it is necessary to evaluate illuminance in work areas based on this standard for the intelligent lighting system. On the other hand, locations such as corridors where illuminance sensors are not installed are places not requiring illuminance provision. They may, therefore, be considered to have low illuminance, and need to have illuminance evaluation by illuminance measurement.

II. Intelligent Lighting System

A. 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.

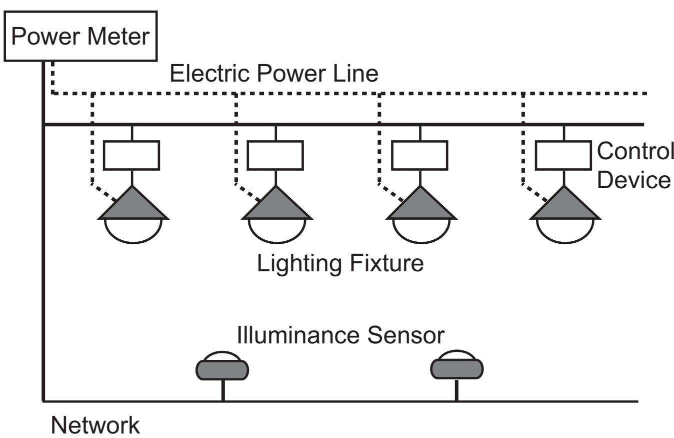


Fig. 1. Configuration of Intelligent Lighting System

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 ligthing 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.

The most significant feature of the intelligent lighting system is that no component exists for integrated control of the whole system; each light is controlled autonomously. For this reason, the system has a high degree of fault tolerance, making it highly reliable even for large-scale offices.

B. Control of the Intelligent Lighting System

In the intelligent lighting system, the algorithm where Simulated Annealing (SA) is improved for lighting control (Adaptive Neighborhood Algorithm using Regression Coefficient: ANA/RC) is used to control luminance intensity for each lighting fixture[9], [10].

SA is the algorithm to obtain the optimal solution by randomly generating the subsequent solution near the present solution, to receive the solution depending on the change in the objective function value as well as on the temperature parameter, and to repeat the transitioning processing. However, using SA is not easy for systems being always necessary to respond to an environmental changes, because SA uses the temperature parameter and cooling method. Then, ANA/RC is proposed. ANA/RC obtains the optimal solution by using a variable neighborhood method without using the temperature parameter that is proposed[9], [10].

It is possible with ANA/RC to provide the target illuminance with minimum power consumption by making luminance intensity for lighting fixtures the design variable and by using the difference between the current illuminance and target illuminance as well as power consumption as objective functions. Furthermore, by learning the influence of each lighting fixture on each illuminance sensor using the regression analysis and by changing the luminance intensity depending on the results, it is possible to promptly change to the optimal luminance intensity. This algorithm is effective to solve the problem which the objective function is near monomodal function and changes in real time.

1) Establish initial parameters including initial luminance intensity.
2) Illuminate each light at the initial luminance intensity.
3) Obtain information on illuminance from each illuminance sensor.
4) Estimate power consumption based on the luminance intensity for each light.
5) Calculate the objective function value in the current luminance intensity.
6) Determine the proper range where the next luminance intensity is generated (proximity or neighborhood) based on the regression coefficient.
7) Randomly generate the next luminance intensity within the neighborhood of (6) and illuminate the lighting fixture at the next luminance intensity.
8) Obtain information on illuminance from each illuminance sensor.
9) Estimate power consumption based on luminance intensity for each light.
10) Calculate the objective function value in the next luminance intensity.
11) Conduct regression analysis based on the amount of change in the luminance intensity for the lighting as well as on the amount of change in illuminance for illuminance sensors.
12) Accept the next luminance intensity if the objective function value turns good. If not, return to the previous luminance intensity.
13) Return to (3).

Through repetition of the above actions, each light learns the factor of influence for each illuminance sensor, each user's target illuminance is provided, and energy consumption is reduced. Furthermore, steps (3) to (12) are one search operation of the luminance value, the time required for each search operation is around 2 second. The abovementioned repetitions return to step (3) instead of step (8) (conducting evaluation of objective function once more) in order to allow for any changes in environment. The objective function is indicated in the Equation 1.

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

$$P = \sum_{i=1}^{m} L_i$$

$$g_j = \begin{cases} 0 & (Ic_j - It_j) \geq 0 \\ R_j \times (Ic_j - It_j)^2 & (Ic_j - It_j) < 0 \end{cases}$$

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

n : number of Illuminance sensors, m : number of Lighting fixtures,
w : weight, P : electric energy, Ic : Current illminance,
It : Target illuminance, L : luminance Intensity,
r : regression coefficient, T : Threshold

As indicate in the Equation 1, the objective function f consists of power consumption P and constraint g_j. The difference between the current illuminance and target illuminance is used for the constraint g_j, and a penalty is imposed only if the target illuminance is not achieved. As a result, the objective function value largely increases as the target illuminance goes further than the current illuminance. $R_j = 0$ is multiplied if the regression coefficient is less than the threshold. With this, if the illuminance sensor with a lower regression coefficient does not achieve the target illuminance, the objective function value does not increase. Therefore, objects for optimization are successfully limited to illuminance sensors to which the lighting gives a strong influence. Furthermore, the weight w value is multiplied for constraint g_j, and it is possible to switch whether or not to prioritize the convergence to the target illuminance over minimization of power consumption by setting the weight w value.

C. The Intelligent Lighting System in Actual Office Environment

Presently, the intelligent lighting system is under a verification experiment in some offices in the aim of commercial use. Introduction offices are shown below.

- Kokuyo Co., Ltd. Eco Liveoffice Shinagawa
  (Tokyo showroom, Minato-ku, Tokyo)
- Mitsubishi Estate Co., Ltd. Area Planning Office
  (Otemachi Building, Chiyoda-ku,Tokyo)
- Mitsubishi Estate Co., Ltd. Management Building Office
  (Otemachi Building, Chiyoda-ku,Tokyo)
- Mitsubishi Estate Co., Ltd. Ecozzeria
  (Shin-Marunouchi Building, Chiyoda-ku, Tokyo)
- Mori Building Co., Ltd. headquarters
  (Roppongi Hills Mori Tower, Minato-ku, Tokyo)
- Mitsubishi Electric Co. headquarters
  (Tokyo Building, Chiyoda-ku,Tokyo)

”Ecozzeria”, a demonstration office for next-generation low-carbon type technology in Shin-Marunouchi Building (Chiyoda-ku, Tokyo) owned by Mitsubishi Estate Co.,Ltd. is one of these buildings. 11 office workers are working in a floorage of 10.1 m $\times$ 7.2 m in Ecozzeria. Each worker is given a fixed seat, and each desk is installed with 1 illuminance sensor each. A meeting space built in the office is installed with 2 illuminance sensors. Fig.2 displays an example of illuminance convergence in Ecozzeria.

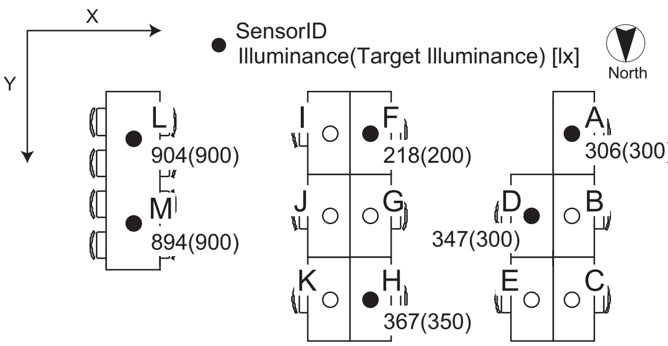


Fig. 2. An example of illuminance convergence in Ecozzeria

In Fig.2, a place displaying a white illuminance sensor implies that a worker is away from the desk. Additionally, since Ecozzeria has windows on the east side, illuminance tends to be higher due to an influence of outside light. The intelligent lighting system, however, allows us to satisfy required illuminance, and as well achieve energy saving by keeps down lighting luminosity of lighting equipments. Fig.2 indicates that the intelligent lighting system satisfies a worker’s required illuminance in actual office environment where each illuminance sensor is installed.

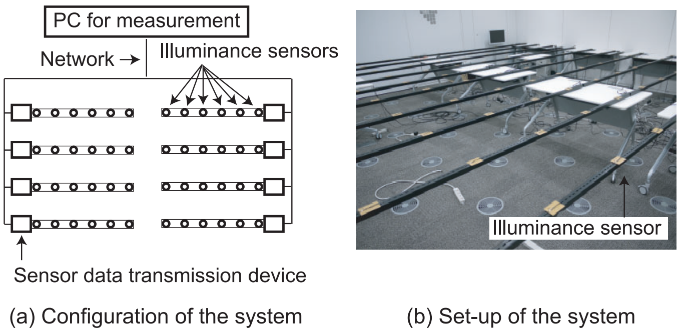
However, illuminance in an area surrounding a place where an illuminance sensor is installed had not been reviewed in the past. In this study, therefore, we conduct verification of illuminance in each worker’s working area and in a place where illuminance sensor is not installed.

III. Evaluation of Intelligent Lighting System in Actual Office Environment

A. Illuminance Distribution Measurement System

Illuminance distribution in an office is often acquired by measurement using multiple illuminance sensors or calculator simulation, and calculation accuracy verification examples have been also reported[11]. Nonetheless, there are so few illuminance sensors in measurement using multiple illuminance sensors, and measurement by computer simulation cannot deal with an influence of outside light changing by season and weather, an influence of direct sunlight changing in a short time, or deterioration or stain differing by lighting equipment so that accurate illuminance evaluation is not easy. Therefore, we structured a system which visualizes the illuminance data obtained from more than 200 illuminance sensors as real-time illuminance distribution.

Illuminance distribution measurement system consists of multiple illuminance measurement module. These illuminance measurement module are composed of 6 illuminance sensors and an 1 sensor data transmission device. Fig.3-(a) shows the composition of illuminance distribution measurement system and Fig.3-(b) shows actual structure of illuminance distribution measurement system.



(a) Configuration of the system (b) Set-up of the system

Fig. 3. Illuminance distribution measuring system

Sensor data transmission device in Fig.3-(a) has A/D converting function for illuminance value measured by illuminance sensors, and transmission function to transmit illuminance value to measurement PC. Therefore, it is possible to aggregate all measured illuminance data into the measurement PC by connecting sensor data transmission device to the measurement PC. Additionally, there is trade-off with measurement frequency of illuminance data through a hub, but in principle, there is no limit in the number of illuminance sensors that can be connected. Measurement PC visualizes illuminance distribution in real time based on the illuminance data received from the sensor data transmission device.

B. *Illuminance Distribution Measurement Experiment*

Illuminance distribution measurement experiment in actual office space was conducted by using illuminance distribution measurement system in order to evaluation of illuminance provided by the intelligent lighting system in actual office environment. A place for this experiment is ”Ecozzeria” in Shin-Marunouchi Building mentioned in Chapter III-B. In this experiment, we use 204 illuminance sensors for measuring the illuminance distribution. Interval of illuminance sensors is set as 50 cm. The actual office has low partitions between desks and it is difficult to place illuminance distribution measurement system on desks. Therefore, illuminance sensors were installed at a position of 125 cm from the floor where there were no shielding objects. Illuminance at a height of 125 cm from the floor is discussed in the following. The experiment environment is shown in Fig.4, and experiment scene in Fig.5.

Two items were conducted in this study; an illuminance distribution measurement experiment under environment with uniform luminosity as lighting environment not using light control and illuminance distribution measurement under the intelligent lighting system environment. In the illuminance distribution measurement experiment under uniform luminosity environment, all lighting equipments’ lighting luminosity was set to uniform luminosity which made illuminance of approximately 1,000 lx at a position of 125 cm from the floor. This illuminance is approximately 750 lx on the desk.

In illuminance distribution measurement experiment in Intelligent Lighting System environment, 10 illuminance sensors named A to M were installed at desks for control of Intelligent Lighting System. These illuminance sensors are respectively called from A to M. Target illuminance of each illuminance sensor is as shown in Fig.4.

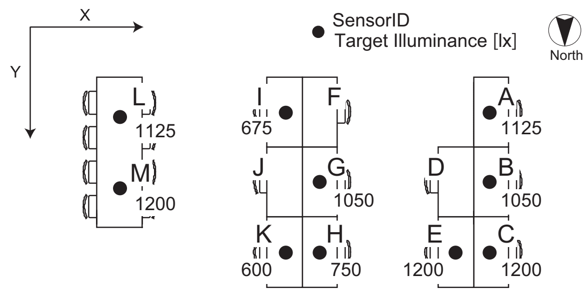


Fig. 4. Experimental environment

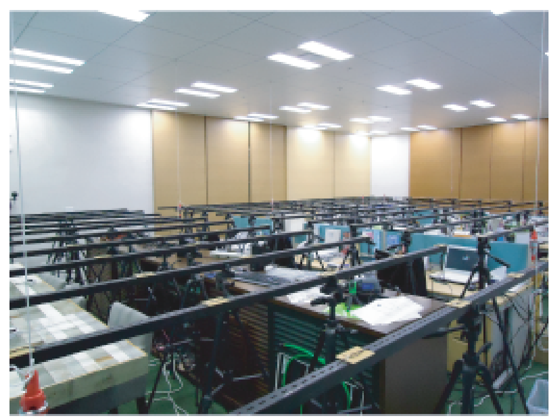


Fig. 5. Experimental photo

Fig.6 shows a result of illuminance distribution measurement experiment under uniform luminosity environment.

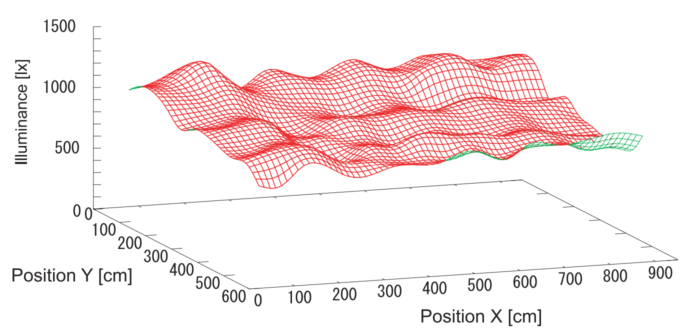


Fig. 6. Illuminance distribution (Uniform luminance)

Furthermore, Fig.6 indicates that illuminance distribution under uniform luminosity environment is almost uniform illuminance environment, but areas directly under lighting equipments have higher illuminance. Area beside the south wall has illuminance increased by 300 lx. It may be considered to be influenced by reflection from a wall, since lighting is installed close to a wall.

Next, the result of illuminance distribution measurement experiment in Intelligent Lighting System environment is shown Fig.7, and target illuminance and measured illuminance of each illuminance sensor are shown in Table.I, and average illuminance at the desks with illuminance sensors installed and in other areas is shown in Table.II.

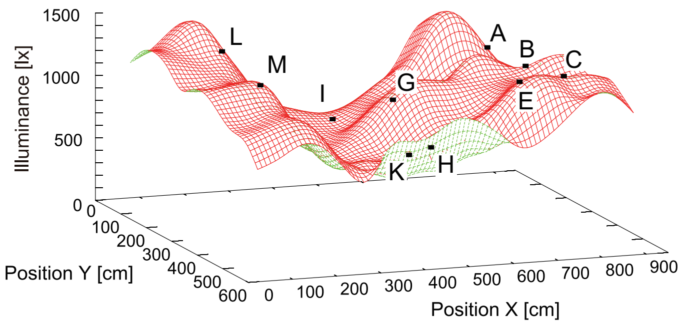


Fig. 7. Illuminance distribution (Using Intelligent Lighting System)

TABLE I
TARGET ILLUMINANCE AND MEASURED ILLUMINANCE OF EACH ILLUMINANCE SENSOR

Illuminance sensor	Target illuminance	Measured illuminance
A	1125	1169
B	1050	1195
C	1200	1249
E	1200	1240
G	1050	1004
H	750	781
I	675	695
K	600	708
L	1125	1174
M	1200	1193

TABLE II
AVERAGE ILLUMINANCE AT THE DESKS WITH ILLUMINANCE SENSORS INSTALLED AND IN OTHER AREAS

	Average illuminance
The desks with illuminance sensors installed	1174
Other Areas	936

Fig.7 indicates that the desks with illuminance sensors installed are provided with individual illuminance and the areas without illuminance sensors generally have lower illuminance in illuminance distribution in Intelligent Lighting System environment. In Table.I, difference between target illuminance and measured illuminance of almost all the illuminance sensors is within 50lx. Considering that illuminance difference which are acknowledgeable for humans in office environment is approximately 50 lx[12], target illuminance is assumed to be achieved for almost all the illuminance sensors. However, for Illuminance Sensors B and K, illuminance difference between target illuminance value and measured illuminance value was over 50 lx. This is because there are illuminance sensors of higher target illuminance values nearby. Illuminance Sensor B's target illuminance is 1050lx, but Illuminance Sensor A's target illuminance is 1125lx, and C's is 1200lx. Illuminance difference in Illuminance Sensor B occurred from demand to achieve these target illuminances. Furthermore, in terms of areas without illuminance sensors, Table.II shows that average illuminance of other areas is lower compared to average illuminance of desks with illuminance sensors installed. In Intelligent Lighting System, energy saving is achievable by setting illuminance lower in the areas where illuminance sensors are not installed.

Illuminance distribution in work areas is discussed next. Work areas mentioned here are desks provided to each worker. As illuminance distribution in work areas, illuminance distribution of Desk G that had especially greater illuminance change within the desk is shown in Fig.8.

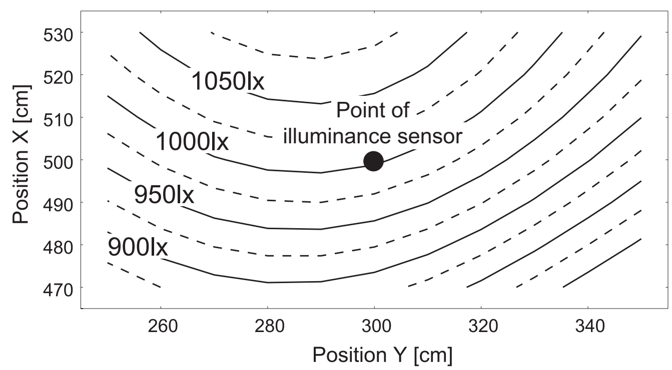


Fig. 8. Work area (Desk G)

Illuminance change within Desk G shown in Fig.8 was approximately 300 lx, and balance rate was 0.73. Balance rate of all other work areas was over 0.7. Considering that work area's balance rate recommended by CIE is over 0.7, illuminance environment of work areas provided by Intelligent Lighting System may be said as appropriate for work.

From the above results, in Intelligent Lighting System, the areas with illuminance sensors installed achieved required illuminance, and the areas without illuminance sensors had lower illuminance. In addition, illuminance change in work areas was indicated to be suitable environment for work in CIE standard.

IV. CONCLUSION

This study mentioned evaluation of illuminance provided by Intelligent Lighting System in actual office environment by using the system which can measure illuminance distribution. As a result, space provided by the intelligent lighting system was appropriate for work, and areas not requiring illuminance provision had lower illuminance. Furthermore, illuminance distribution was formerly obtained by computer simulation in actual office space, but actual measurement helped obtain more precise illuminance distribution.

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