An Intelligent Lighting System to Realize Individual Lighting Environments Based on Estimated Daylight Distribution

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

Takuro YOSHII
Graduate School of Engineering
Doshisha University
Kyoto, Japan
tyoshii@mikilab.doshisha.ac.jp

Tomoyuki HIROYASU
Department of Life and Medical Sciences
Doshisha University
Kyoto, Japan
tomo@is.doshisha.ac.jp

Masato YOSHIMI
Department of Science and Engineering
Doshisha University
Kyoto, Japan
myoshimi@mail.doshisha.ac.jp

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

***Abstract*—When we introduced a lighting system to realize individual lighting environments into real office environments, difficulties arose in placing illuminance sensors on users' workplanes. This study hence proposes a new approach to control a lighting system intended to realize individual lighting environments without placing illuminance sensors on users' workplanes. This system uses illuminance sensors for measuring not the illuminance on workplanes but that of daylight: it optimizes lighting based on simulations for different luminous intensities of lighting and patterns of daylight illuminance distribution which are estimated from measurements by daylight illuminance sensors. An experiment to converge illuminance at target positions into target illuminance levels was conducted in a setting with 15 fluorescent lights and 9 illuminance sensors, which was intended to simulate a real office environment. The result indicated that such a system can realize illuminance levels required by individual users with minimum power consumption responding to changing daylight conditions.**

***Index Terms*—lighting, intelligent lighting system, illuminance distribution, daylight, optimization, illuminance sensor**

I. INTRODUCTION

With the development of electronic parts and information technologies, microcomputer chips are now built into many machines. In this context, there have been many attempts to develop an intelligent system which enables the machine itself to autonomously control its operation to suit user or environmental requirements. In the field of lighting and air conditioning, however, the introduction of intelligent systems has been rather slow compared to other products from such concerns as installation costs. Yet at last in recent years, attempts of intelligent designs have increased also in lighting systems, intended, for instance, to realize lighting patterns meeting different user requirements or to minimize energy consumption. One example is a residential lighting fixture with automatic brightness adjustment function by sensor[1]. In this system, an illuminance sensor built into the lighting fixture detects reflection by the surrounding surfaces and natural daylight so that, based on the measurement, the system may control the luminous intensity of the lighting to keep the illuminance within the area at a certain level. Such a system can prevent the luminous intensity from being higher than necessary so as to minimize energy consumption.

This lighting system, however, cannot provide brightness (illuminance) at the level and the point as desired by the user, as long as the illuminance sensor is positioned on the lighting fixture. On the other hand, it has been reported that providing the illuminance most appropriate to the task of each worker is an effective choice for the improvement of office environment[2]: to realize energy efficiency and to improve optical environment for each worker, the use of task-ambient lighting systems will be an effective approach.

But in reality, task-ambient lighting systems are not widely accepted in Japanese offices because (1)typical office buildings are equipped with ceiling lighting fixtures which can ensure a desktop illuminance of 750 lx without a task-ambient lighting, and (2)most companies are not willing to pay additional costs for purchasing task-ambient lightings, as well as consider that task-ambient lighting systems spoil the visual impression of the office.

Against this backdrop, the authors have proposed an intelligent lighting system which can provide brightness as required by users at any given points specified by users, depending only on ceiling lighting fixtures[3], [4]. With this intelligent lighting system, each user specifies a target illuminance level for an illuminance sensor which is to be placed on the workplane, then the system will realize the target illuminance level. The intelligent lighting system, composed of a lighting fixture, a control device, an illuminance sensor and a wattmeter, can realize any lighting patterns as required by the user independent of electrical wiring. The intelligent lighting system has proven successful in our laboratory experiments[5].

Toward the commercialization of our intelligent lighting systems, currently verification experiments are underway in several offices in Tokyo[6]. The results so far indicate that there are cases where it is difficult to place an illuminance sensor on the user’s workplane. In this study, we will propose a new approach for controlling intelligent lighting systems to realize an individualized lighting environment without a need to place an illuminance sensor on the user’s workplane. Further, an operational experiment under an environment simulating a real office is conducted to verify the effectiveness of the proposed system.

II. INTELLIGENT LIGHTING SYSTEM

A. *Construction of 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.

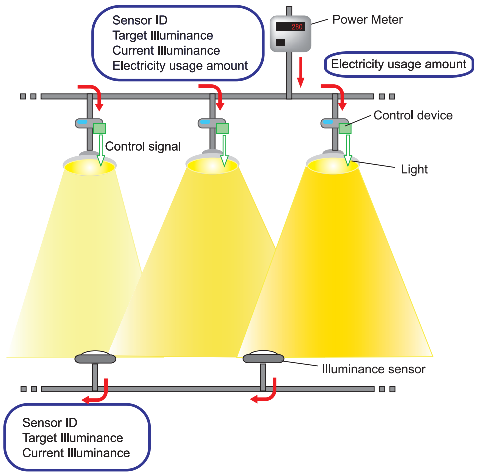

Fig. 1. Configuration of Intelligent Lighting System

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 lighting pattern. Also, with the intelligent lighting system, positional information for the lights and illuminance sensors is unnecessary. This is because the lights learn the factor of influence to the illuminance sensors, based on illuminance data sent from illuminance sensors. In this fashion, each user’s target illuminance can be provided rapidly.

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. *Adaptive Neighborhood Algorithm using Regression Coefficient(ANA/RC)*

The control algorithm is a critical element for the control of an intelligent lighting system. The speed of convergence to the target illuminance as well as its accuracy depends largely on the lighting control algorithm. As the best algorithm presently available for lighting control, we have proposed an Adaptive Neighborhood Algorithm using Regression Coefficient (ANA/RC)[7], which was developed by adapting the Stochastic Hill Climbing method (SHC) specifically for lighting control purposes.

In ANA/RC, the design variable is the luminous intensity of each lighting: the algorithm aims to minimize the power consumption while keeping the illuminance at the target level or above. It further enables the control system to learn the effect of each lighting on each illuminance sensor by regression analysis and, by changing the luminous intensity in response, enables a quick transition to the optimum intensity.

The following is the flow of control by ANA/RC:

1) Each lighting lights up by initial luminance.
2) Each illuminance sensor transmits illuminance information (current illuminance, target illuminance) to the network. The electrical power meter transmits power consumption information to the network.
3) Each lighting acquires the information from step 2, and conducts evaluation of objective function for current luminance.
4) Neighborhood is determined, which is the range of change in luminance based on factor of influence and illuminance information.
5) The next luminance within the neighborhood is randomly generated, and the lighting lights up by that luminance.
6) Each illuminance sensor transmits illuminance information to the network. The electrical power meter transmits power consumption information to the network.
7) Each light acquires the information from step 6, and conducts evaluation of objective function for next luminance.
8) A regression analysis is conducted and the level of influence is estimated.
9) If the objective function value is improved, the next luminance is accepted. If this is not the case, the lighting returns to the original luminance.
10) Steps 2〜9 are one search operation of the luminance value, which is repeated.

A search operation process (requiring about 2 seconds) consists of steps 2) through 9) above: by iterating this process, the system continues to learn how the lighting affects the illuminance sensor measurement until it realizes the target illuminance with minimum power consumption. Furthermore, by using the influence level found in step 8) as a basis for the evaluation and generation of the next illuminance value, the system can quickly optimize illuminance.

Next, we will see the objective function used in this algorithm. The purpose of the intelligent lighting system is to achieve each user’s desired illuminance, and to minimize energy consumption. Thus, it can be understood as an optimization problem in which each light optimizes its own luminance. Following from this, the luminance of each light is considered a design variable, under the constraint of the user’s target illuminance, in resolving the problem of optimization to minimize energy consumption. For this reason, the objective function is set as in Eq. (1).

$$f = P + w\sum_{i=1}^{n} g_i \tag{1}$$

$$g_i = \begin{cases} (It_i - Ic_i)^2 & I^* \leq |It_i - Ic_i| \\ 0 & otherwise \end{cases} \tag{2}$$

P: Power consumption, w: Weight, Ic: Current illuminance
It: Target illuminance, n: Number of target points
I^*: Threshold on illuminance difference

The objective function was derived from amount of electric power P and illuminance constraint g_j. Also, changing weighting factor w enables changes in the order of priority for electrical energy and illuminance constraint. The illuminance constraint is decided so that a difference between current illuminance and target illuminance within a threshold, as indicated by Eq. (2). The threshold value is set as a 50 lx.

Since this intelligent lighting system uses an autonomous distributed-control algorithm, particular cases of installation may use either distributed control or centralized control.

III. VERIFICATION EXPERIMENTS IN REAL OFFICE ENVIRONMENTS

From around 2009 onward, we have conducted experiments to verify the effectiveness of the intelligent lighting system in several offices in Tokyo. Fig.2 shows how the intelligent lighting system is used in an office of Mori Building Co., Ltd. (Roppongi Hills Mori Tower). As shown in the photo, an illuminance sensor is placed on the workplane and the user presets the target illuminance. This enables the intelligent lighting system to realize the targeted brightness on the user’s workplane using the control algorithm described in the preceding chapter.

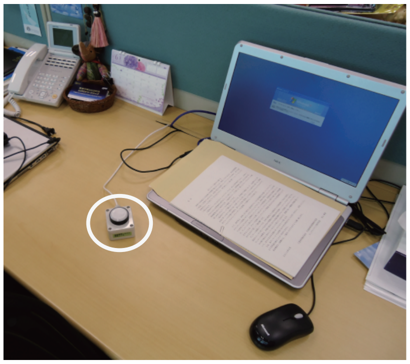

Fig. 2. An experimental intelligent lighting system in a real office

In our experiments in some offices, however, it was found difficult to place illuminance sensors on user workplanes due to mounting documents. In those cases, illuminance sensors were placed at such points as a corner or a partition top. Fig.3 shows an example of an illuminance sensor placed on top of a partition. Positioning the illuminance sensor this way makes it impossible for the system to realize the target illuminance on the user’s workplane.

Fig. 3. A situation prohibiting the placement of an illuminance sensor on the workplane (example)

Therefore, to solve this problem while maximizing the workspace available for the user, we propose a new control algorithm for intelligent lighting systems.

IV. OPTIMAL CONTROL OF LIGHTING BASED ON ESTIMATED DAYLIGHT DISTRIBUTION PATTERNS

A. *Configuration of the proposed system*

As mentioned in the preceding chapter, it was found difficult in some real office environments to place illuminance sensors on users’ workplanes. Hence, we propose a new system to realize the desired illuminance at any given point specified by each user with minimum power consumption without placing an illuminance sensor on the user’s workplane. To realize the target illuminance at the workplane which does not have an illuminance sensor, the system estimates illuminance there by simulation. Further, to maximize the accuracy of simulation, illuminance sensors are set in readily available spaces such as partition tops, and the system estimates patterns of daylight illuminance based on the distribution of illuminance measurements. Unlike earlier intelligent lighting systems, this system requires data on user and illuminance sensor positions for making simulations. Here, the point where the target illuminance should be realized is typically the user’s workplane. Therefore the positions of target points where certain illuminance levels are desired by users will be readily known since desk positions are usually fixed.

The proposed system will be composed of lighting fixtures, illuminance sensors and a central control device. In the proposed system, an optimum lighting pattern is found based on simulations using illuminance sensor measurement data, then the luminous intensity of each lighting is determined. Since this makes it impossible to use a distributed control approach with control devices built into each lighting fixture, a central control device is used unlike our earlier intelligent lighting systems. Illustrative configuration of the proposed system is shown in Fig.4, which is a view of a room from the top.

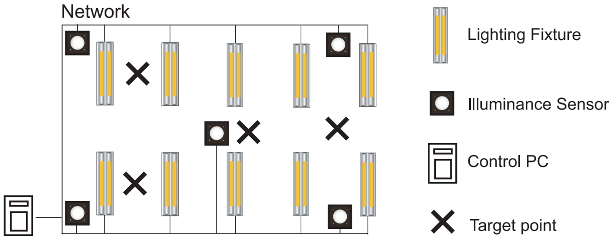

Fig. 4. Illustrative configuration of the proposed system

B. Proposed system control

The proposed system estimates the effect of light from sources other than the lightings under control, such as daylight, based on the measurement data obtained from all illuminance sensors in different positions within the room. Then, in view of the distribution of illuminance from daylight, it determines an optimum lighting pattern based on a simulation. For this simulation, the Stochastic Hill Climbing method (SHC) is used as it was in preceding intelligent lighting systems. Although SHC tends to find a local optimum solution if the objective function is multimodal, studies have indicated that a good solution can be obtained with SHC by limiting the area of neighborhood to an appropriate range, which is defined as a range of generation of next solutions.

By using this method, the system will be able to provide the desired illuminance results without setting illuminance sensors on users ' workplanes. The flow of control of the proposed method is shown below. Here, illuminance sensor positions and target positions are given initially.

1) Calculate the optimum luminous intensity of each lighting to realize the target illuminance at target positions with minimum power consumption based on illuminance calculation, then turn on each lighting with the calculated luminous intensity (the luminous intensity from daylight is assumed to be 0 lx).
2) Obtain illuminance data from illuminance sensors.
3) Calculate the difference between the calculated illuminance and the actual illuminance measured at each illuminance sensor position, which should be the illuminance from daylight at the sensor position.
4) Estimate the distribution of daylight in the entire room based on the daylight illuminance values obtained from the above calculation, and then estimate the illuminance from daylight at each target position.
5) For each target position, optimize the luminous intensity of the lighting so as to bring its illuminance as close as possible to the difference between the target illuminance and the illuminance from daylight.
6) Repeat steps 2) through 5).

Using this method, even when illuminance sensor positions do not coincide with the points where the desired illuminance should be realized, the system can realize the target illuminance values responding to changing daylight conditions with minimum power consumption. Just as in our previous intelligent lighting systems, the objective function of Eq.(1) is used, where illuminance Lc is the sum of the illuminance from the lighting (lighting illuminance) and the illuminance from natural daylight (daylight illuminance).

$$Ic_i = Il_i + Id_i \tag{3}$$

Il: Illuminance from lighting, Id: Illuminance from daylight

Lighting illuminance is calculated using an illuminance simulator described in the following section, while daylight illuminance at any given point is calculated using a daylight simulator described in the following section. By using these two simulators, the optimization problem expressed by Eq.(1) is solved to realize lighting control.

C. Illuminance simulator

To calculate illuminance at a given point in a given room, different approaches have been studied including the point-by-point method and the lumen method calculations using Monte Carlo method[8], which are known to be capable of realizing a high level of accuracy. Still, to ensure a high level of accuracy with these methods require defining many parameters such as the luminous flux of lighting, maintenance factor, luminous intensity distribution curve or reflection by walls, of which values are not readily known in most real-world environments.

Therefore, to enable highly accurate simulations in a simplified method, the proposed approach uses only a limited number of parameters. Given that the target points where a certain illuminance level is required are on fixed workplanes, here we need to simulate only illuminance at specific positions rather than at any arbitrary positions. In the proposed approach, the actual illuminance at a particular point is measured with the relevant lighting illuminated at a particular luminous intensity, and the level of influence by the lighting at that point is stored on a database. Then based on this value, illuminance at that particular point under any given lighting pattern can be calculated. At the illuminance sensor positions, the daylight illuminance can be calculated as a difference between the measured illuminance and the lighting illuminance.

D. Daylight simulator

Different approaches have been studied to calculate daylight illuminance distribution[9], [10], which use such factors as the position of the sun, the amount of clouds, and the transmittance of the windowpane material to calculate daylight distribution patterns. Yet they either assume an environment without a window blind or require detailed data on the effects of blinds.

Also, dust on blinds may change the reflectance of the blind to spoil the accuracy of simulation.

Therefore in the proposed method, illuminance sensors are positioned in spaces where they can be placed readily and the daylight illuminance distribution function is estimated using the least square method based on the daylight distribution assessed as described above.

E. *Derivation of a model equation*

Plenty of illuminance sensors were set in the experimental environment as shown in Fig.5 and daylight illuminance was measured by each sensor. A model equation was derived based on the daylight illuminance measurements on sunny, cloudy and rainy days over a period from October to January.

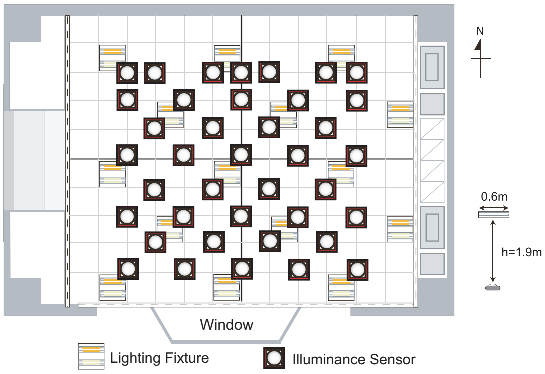

Fig. 5. Daylight illuminance measurement system

After making many trials and errors, we derived a model equation which best expresses the indoor daylight illuminance distribution. Eq. (4) is the derived model equation. In the proposed method, the daylight illuminance distribution function is estimated based on the model equation, when positional coordinates are (x,y) and the daylight illuminance at that position is z.

$$z = \beta_0 + \beta_1 x^4 y^3 + \beta_2 x^3 y^4 + \beta_3 x^3 y^2 + \beta_4 x^2 y^4 + \beta_5 x y^3 + \beta_6 x y^2 + \beta_7 y \quad (4)$$

V. SUMMARY OF AN OPERATIONAL EXPERIMENT

An operational experiment was conducted for a total of 9 hours between 7:00 and 16:00 on December 19, 2010, which was a sunny day. The proposed system was constructed and its validity was tested for verification. Illuminance sensors were set at regular intervals and the points for which users will specify desired illuminance levels (hereinafter called “target points”) were defined.

The experiment used 9 illuminance sensors and assumed 5 users with target points arranged as shown in Fig. 6. The target points included points A, B, C, D and E, for which the target illuminance was set at 400 lx, 500 lx, 550 lx, 600 lx and 700 lx respectively.

Illuminance data were taken every second and lightings were turned out once in every minute. Since the purpose of turning out lights here is only to allow comparison between the daylight illuminance distribution as estimated by the proposed system and the actual distribution of illuminance from daylight, they were never turned out while operating the system under the proposed method. For the experiment, window blinds were arranged 45 degrees outward and neutral white fluorescent lamps were used of which luminous intensity was variable between 401 cd and 1336 cd.

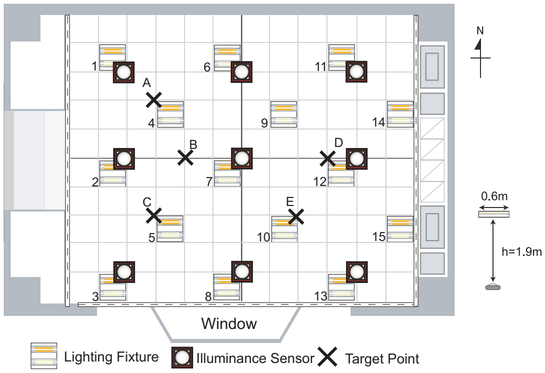

Fig. 6. Experimental environment

In the operational experiment, the lighting pattern was changed every 30 seconds to verify whether the target illuminance levels are constantly realized at target points.

VI. EXPERIMENT RESULTS AND DISCUSSIONS

Fig.7 shows history of the illuminance data at target points A, B, C, D and E. Fig.8 shows history of the daylight illuminance data, measured once in every minute with lights turned out. Fig.9 shows history of the luminous intensity data of lights 4, 5, 7, 10 and 12 which are located near some target point.

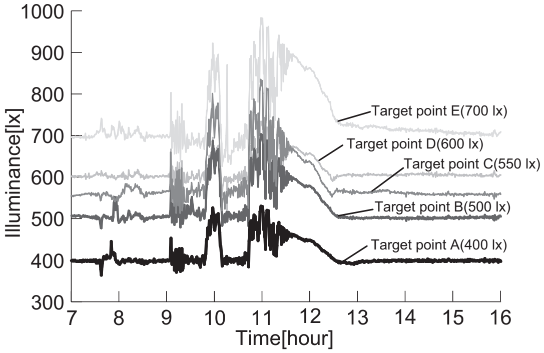

Fig. 7. History of the measured illuminance data

Fig.7 indicates that target luminance levels were constantly achieved after 12:30. There were, however, some periods when target illuminance levels were not achieved: particularly around 10:00 and from 11:00 until around 12:20, the actual illuminance levels were higher than target values. Noting that, let us examine Fig.8 and Fig.9: Fig.8 indicates that in those periods when target illuminance was not achieved, the effect of daylight illuminance was significant. Also, as one can see from Fig.9, the luminous intensity levels of the lightings were kept

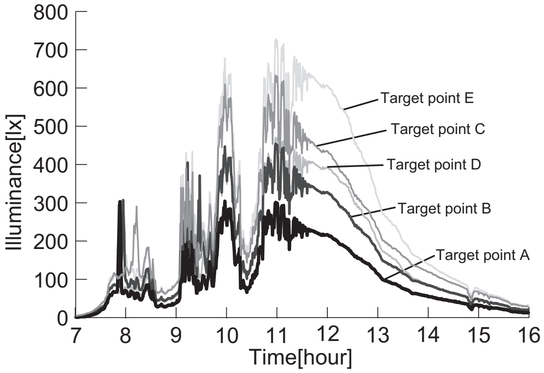

Fig. 8. History of the measured daylight illuminance data

at a minimum level during such periods. These results indicate that when actual daylight illuminance is too large, it was simply physically impossible to realize the target illuminance levels. For this, from the history of the measured illuminance data in the periods between 7:00 and 9:40 and after 12:30, we can learn that the luminous intensity of each lighting changes as the measured daylight illuminance changes, and thus the target illuminance values can be achieved.

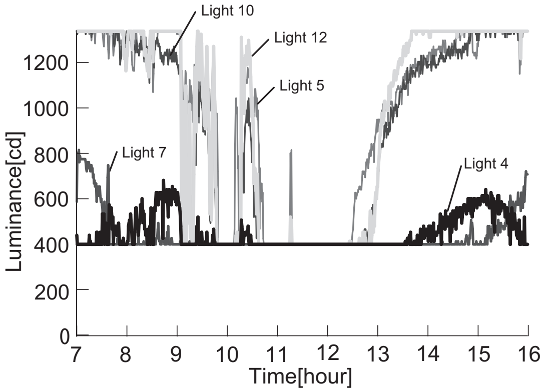

Fig. 9. History of the luminous intensity in the proximity of target points

Next, we will examine the energy efficiency of the proposed method. Fig.10 shows history of the luminous intensity data of lightings number 9 and 11 which are distant from target points.

Fig.10 indicates that lightings distant from target points illuminated at a minimum intensity, demonstrating the energy efficiency of the proposed system. These results demonstrated that the proposed method can provide desired illuminance levels on workplanes without setting illuminance sensors on those workplanes while saving energy.

VII. CONCLUSION

In this paper, we proposed a new control algorithm for an intelligent lighting system which realizes desired illuminance levels on workplanes based on illuminance distribution patterns estimated from illuminance data obtained by illuminance sensors placed on readily available spaces such as partition tops instead of workplanes.

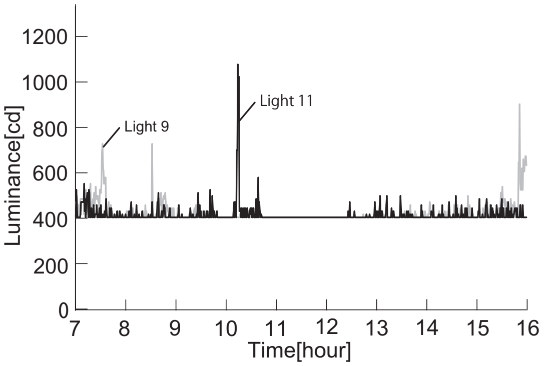

Fig. 10. History of the luminous intensity distant from target points

To verify the validity of the proposed method, an operational experiment was conducted in an environment simulating a real office. The experiment demonstrated that the method we propose can realize desired illuminance levels with energy efficient lighting patterns by estimating daylight from windows even when illuminance sensor positions do not coincide with the points where users wish to realize desired illuminance levels. These results demonstrate that individualized illuminance environments can be realized even where illuminance sensors cannot be placed on workplanes.

REFERENCES

[1] H. Yoshida and T. Mannam :Technologies — Panasonic Electric Works — Panasonic - "Residential Lighting Fixture with Automatic Brightness Adjustment Function by Sensor", panasonic, Technical Report Vol. 57, No. 4, 2009
http://panasonic-electric-works.net/technologies/report/574e/main02.html

[2] P. Boyce and N. Eklund and N. Simpson :"individual Lighting Control Task Performance, Mood, and Illuminance", J. of the Illuminating Engineering Society, pp.131-142, 2000.

[3] M. Miki, T. Hiroyasu, and K.Imazato :"Proposal for an intelligent lighting system, and verification of control method effectiveness", Proc. IEEE CIS, pp.520-525, 2004.

[4] M. Miki, K. Imazato, and M. Yonezawa :"Intelligent lighting control using correlation coefficient between luminance and illuminance", Proc. IASTED Intelligent Systems and Control, vol.497, no.078, pp.31-36, 2005.

[5] M.Miki, Y.Kasahara,T.Hiroyasu and M.Yoshimi :"Construction of Illuminance Distribution Measurement System and Evaluation of Illuminance Convergence in Intelligent Lighting System", IEEE Sensors2010 Acoustic and Optical Sensing Systems, 2010.

[6] S.Inoue, MITSUBISHI ESATE COMPANY Ltd,:Towards "the City of the Future"
http://www.jetro.org/documents/green_innov/Shigeru_Inoue_Presentation.pdf

[7] S. Tanaka, M. Miki, T.Hiroyasu and M.Yoshikata :"An evolutional optimization algorithm to provide individual illuminance in workplaces",Proc:Systems Man and Cybernetics, 2009. SMC 2009. IEEE International Conference on ", pp.941-947, 2009.

[8] Y. Ohtani, M. Ohkawa, A. Uchida and T. Yamaya :"Illuminance Calculation Using Monte Carlo Method", J. Light &Vis. Env., Vol. 24, No.1, pp.1_42-1_49, 2000.

[9] C. Reinhart and S. Herkel :"The simulation of annual daylight illuminance distributions — a state-of-the-art comparison of six RADIANCE-based methods", Trans. Energy and Buildings, Volume 32, Issue 2, pp.167-187,2000.

[10] D. Li, G. Cheung and C. Lau :"A simplified procedure for determining indoor daylight illuminance using daylight coefficient concept", Trans. Building and Environment Volume 41, Issue 5,pp. 578-589, 2006.