Construction of Intelligent Lighting System Providing Desired Illuminance Distributions in Actual Office Environment

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Abstract. An Intelligent Lighting System providing desired illuminance distributions at minimum electrical power was constructed in the actual office environment. The place of construction is the Area Planning Office in the headquarters building of Mitsubishi Estate Co., Ltd. in Otemachi, Tokyo. The floor area is about 240 square meters, and 26 lighting fixtures and 22 illuminance sensors are installed. One lighting fixture consists of neutral fluorescent lamp and light bulb fluorescent lamp, and the color temperature can be changed for each fixture. These devices are connected with the control PC and operate with an optimization algorithm. With the constructed system, individual illuminance was successfully provided to each office worker.

Key words: Lighting Control, Optimization, System Construction, Illuminance, Office Environment

1 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].

Intelligence in lighting systems also began to progress from the viewpoints of realization of illumination patterns that respond to various user requirements as well as of reduction in power consumption. One example is the self control system[2]. With the self control system, the influence by reflected light as well as by daylight is measured with the illuminance sensor built in a light, depending on which the brightness of a lighting fixture is controlled. With this system, it is possible to maintain brightness at a constant level on the desk surface in the measured area, to refrain brightness more than intended at the time of design, and to realize power savings. However, this kind of system controls lights by segment by using fixed illuminance sensors and lights can only be controlled by segment unit; therefore it is not easy to provide discretionary illuminance at a discretionary place.

On the other hand, 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[3]. 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, an intelligent lighting system is proposed by the authors. The intelligent lighting system consists of lighting fixtures equipped with a microprocessor, illuminance sensors and an energy meter connected to the network. By controlling each light based on the optimization algorithm that determines luminance intensity, brightness required by a user is provided to a discretionary place. Verification experiments for this system were conducted in the laboratory, which clarified that it is possible to provide required illuminance at several different places under the environment of 15 lights. However, there are far more lights as well as places requiring illuminance in actual offices. For this reason, it is necessary to conduct this kind of large-scale verification experiments upon practical application of the intelligent lighting system. Therefore, the intelligent lighting system was constructed in the actual office in Tokyo, in order to verify the possibility to provide required illuminance.

2 Construction of Intelligent Lighting System in Actual Office Environment

2.1 Purpose of System and Environment for Construction

As described earlier, it is necessary to conduct large-scale verification experiments in an actual office upon practical application of the intelligent lighting system. For this purpose, the intelligent lighting system was constructed in an actual office. The intelligent lighting system constructed is referred to as the “ system. ”

The place of construction is the Area Planning Office in the Otemachi Building (Chiyoda City, Tokyo) owned by Mitsubishi Estate Co., Ltd. In the Area Planning Office, 22 office workers are working on the 16m×15m floor. Each office worker is provided a fixed seat, and one illuminance sensor is installed on each of their desk surfaces. As light source, 26 lighting fixtures consisting of neutral fluorescent lamp (color temperature: 5000K) and one light bulb fluorescent lamp (color temperature: 3000K) manufactured by Mitsubishi Electric Co., Ltd. are installed. The lighting layout and illuminance sensor layout in the Area Planning Office is indicated in Fig. 1.

Under the environment described in the above, the environment to control lights simply by setting illuminance and color temperature required by a user was constructed.

2.2 Overview of the Constructed System

The system provides illuminance required by each office worker (target illuminance) at minimum power consumption with the optimization algorithm based on illuminance and power consumption for each illuminance sensor. It is also

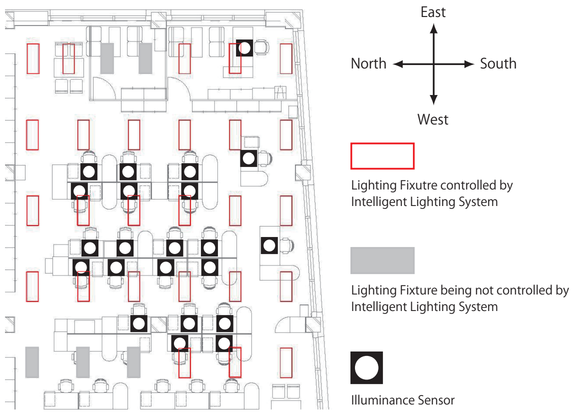

Fig. 1. Environment for construction

possible with the system to individually change color temperature by changing the ratio of luminance intensity for neutral fluorescent lamps and light bulb fluorescent lamps comprising each lighting fixture. However, the color temperature is not controlled.

The target illuminance is established for each illuminance sensor possessed by each office worker. It means that each lighting fixture is controlled so that brightness around the illuminance sensor reaches the target illuminance. Each lighting fixture consists of neutral fluorescent lamp and light bulb fluorescent lamps, and the target illuminance is achieved by controlling the sum of their luminance intensity. The sum of luminance intensity for neutral fluorescent lamps and light bulb fluorescent lamps is referred to as the" luminance intensity for the lighting fixture "and the ratio of luminance intensity as the" ratio of illumination. "

2.3 Composition of the Constructed System

The hardware composition for the system includes one control PC, 26 lighting fixtures (neutral fluorescent lamp and light bulb fluorescent lamp), 3 dimmers (10 channels are mounted on each dimmer), 22 illuminance sensors, and two A/D converters. Connection of the above device is indicated in Fig. 2.

It is common in Japan to control the luminance intensity of fluorescent lamps with the Pulse Width Modulation (PWM) method. Therefore, each lighting fixture was connected with a dimmer in order to control luminance intensity for each lighting fixture. The dimmer changes the duty ratio for pulse waves to 256 steps based on the PWM method and sends it to each lighting fixture. Lighting becomes brighter when a pulse wave with a high duty ratio is sent, and darker when a pulse wave with a low duty ratio is sent.

Therefore, it is possible to control luminance intensity for each lighting fixture from a control PC by connecting the control PC with the dimmer. Since a dimmer is able to change a duty ratio independently for each channel, it is possible to independently control the luminance intensity for each light.

As described earlier, information on illuminance and power for each illuminance sensor is necessary to control the intelligent lighting system. Each illuminance sensor was connected to the control PC in order to obtain information on illuminance. However, since information on illuminance from the illuminance

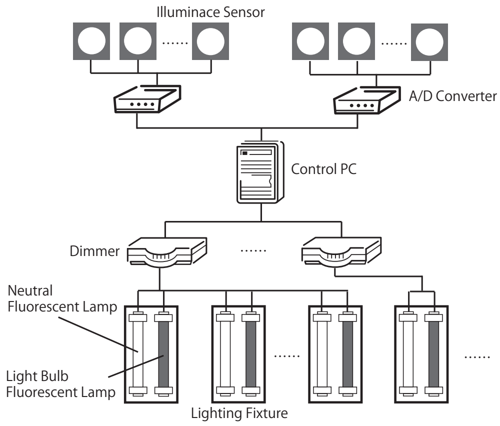

Fig. 2. The hardware composition for the system

sensor used is output by analog signals, they are converted to digital signals through the A/D converter then sent to the control PC.

On the other hand, a device that can obtain real-time information on power over the network is not available; therefore such information is presumed based on the sum of luminance intensity for each light since it is in a proportional relationship with electric energy. Since the luminance intensity for each light is controlled by the control PC, it is possible to operate the system more effectively than using the electric meter. It is noted however that electric energy can be estimated more accurately by adding electric energy for all fluorescent lamps presumed in accordance with the calibration curve for luminance intensity and electric energy for each lamp. However, accurate electric energy is not always necessary at the time of optimization for the purpose of minimizing power consumption.

2.4 Control of the Constructed System

Control Method In the 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[5].

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.

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.

The luminance intensity for each lighting fixture obtained from the above processing is distributed at the ratio of illumination as the luminance intensity for neutral fluorescent lamps and light bulb fluorescent lamps in accordance with the established color temperature. This ratio of illumination is calculated based on the preliminary experiment where the color temperature is measured by changing the luminance intensity for neutral fluorescent lamps and light bulb fluorescent lamps at a constant level. The ratio of illumination is indicated in Fig. 3 as the proportion of the luminance intensity for neutral fluorescent lamps against the luminance intensity for lighting fixtures. In Fig. 3, the ratio of illumination is not plotted from 3000K to 3300K and from 4600K to 5000K. This is because the dimming range for each fluorescent lamp is limited and the ratio of illumination based on the color temperature in the above cannot be achieved.

With the above processing, it is possible to achieve the target illuminance with the established color temperature.

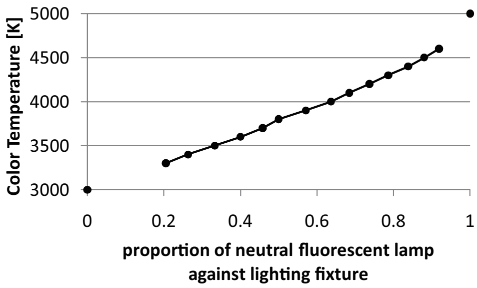

Fig. 3. Change in color temperature

Understanding of the Influence with the Regression Analysis To understand the influence of each lighting fixture to each illuminance sensor is important to shorten the search time until achieving the target illuminance, because each lighting fixture is able to change the luminance intensity depending on adjacent illuminance sensors by understanding the influence on each illuminance sensor. With ANA/RC, therefore, the regression analysis is conducted to understand the influence of each lighting fixture on each illuminance sensor. As a result of this, the influence can be quantified as the regression coefficient.

Control Flow The flow of processing in ANA/RC is indicated in the following:

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).

By making the above (3) to (12) as the first step of searching (approximately two seconds) and by repeating this processing, the influence of each light to each illuminance sensor is understood, achieving the target illuminance only with necessary lighting.

Let's discuss on the objective function next. The purpose of the system is to achieve the target illuminance while minimizing power consumption. Therefore, these are formulated as the objective function. The objective function is indicated in the Equation 1.

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

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

$$g_j = \begin{cases} 0 & 0 \leq (Lc_j > Lt_j) > 0 \\ R_j (Lc_j - Lt_j)^2 & (Lc_j - Lt_j) \leq 0 \end{cases}$$

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

n : number of Illuminance sensors, m : number of Lighting fixtures
w : weight, P : electric energy, Lc : Current illminance
Lt : Target illuminance, Cd : 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.

Let's now discuss on the range where the next luminance intensity is generated (neighborhood). In ANA/RC, the same neighborhood is not used for all lights but multiple neighborhood are properly used depending on situations. Specifically, the neighborhood for the lighting with a high regression coefficient with a sensor that does not achieve the target illuminance is from −1% to 12% of the current luminance (brightening neighborhood). On the contrary, the neighborhood for the lighting with a low regression coefficient with all sensors is from −10% to 1% of the current luminance (dimming neighborhood). In the case that the target illuminance for a sensor with a high regression coefficient is achieved, it is from −2% to 2% of the current luminance (neutral neighborhood). By properly using the three kinds of neighborhood depending on situations, it is possible to promptly achieve the target illuminance while flexibly responding to the change in the environment.

3 Verification of the Operation of the Constructed System

How closely the system was able to provide illuminance compared with the target illuminance required by a user is verified. Upon verification, three out of 22 office workers were extracted, including one who established a rather high target illuminance (Office Worker A), one who established a rather low target illuminance (Office Worker B) and one who regularly changed the target illuminance (Office Worker C). Daily transition of the target illuminance and current illuminance is reviewed.

Fig. 4(a) shows the transition of the target illuminance and current illuminance for the office worker who established the target illuminance at 550 [lx], Fig. 4(b) shows the office worker who established the target illuminance at 300 [lx] and Fig. 4(c) shows the office worker who regularly changed the target illuminance. The vertical axis indicates the illuminance [lx] and the horizontal axis indicates the time.

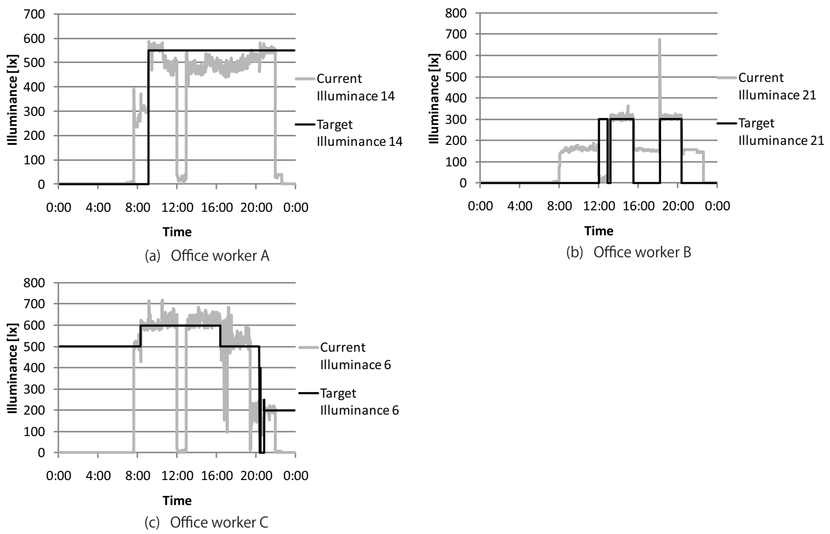

Fig. 4. Transition of the Target Illuminance and Current Illuminance

There is a timeframe when the target illuminance is set at 0 [lx] in Fig. 4, indicating the situation where the office worker is not at the desk. The timeframes from 0:00 to 7:30, from 12:00 to 13:00, and from 22:30 to 24:00 are indicating values close to 0 [lx] for all current illuminance regardless of the target illuminance. This is because all lights are turned off by the switch, since work is not executed during these timeframes. During the timeframe from 7:30 to 9:00, only the illuminance during daylight from windows is measured.

For the office worker indicated in Fig. 4(a), the target illuminance was set at 550 [lx] at 9:00. It is confirmed that illuminance close to this target illuminance was successfully achieved except during the timeframe when the lights were turned off for lunch break.

The target illuminance was set at 300 [lx] during the timeframes when the office worker was at his desk as indicated in Fig. 4(b). The target illuminance increased from 0 [lx] to 300 [lx] when he returned to his desk at 18:30. At this time, the illuminance reached nearly 700 [lx]. This is because the lights that had been turned off were illuminated again all at once. However, the illuminance then converged to the target illuminance as a result of system control. It is confirmed that illuminance close to the target illuminance was achieved except in the above timeframe. On the other hand, the target illuminance was set at 0 [lx] when the office worker was not at his desk, while the illuminance was not 0 [lx]. This is because necessary lights were illuminated in order to achieve the target illuminance for adjacent office workers.

The office worker indicated in Fig. 4(c) set various target illuminance depending on the time. In this case as well, it is confirmed that illuminance close to the target illuminance was achieved except the timeframe from 16:30 to 17:00. The target illuminance was also set at 500 [lx] and 200 [lx] in early mornings and late evenings, because the office worker forgot to set the target illuminance at 0 [lx] when he left his desk. The current illuminance largely fell below the target illuminance during the timeframe from 16:30 to 17:00, because the receiver of illuminance sensor was covered by documents, etc. and illuminance might have not been properly obtained.

In accordance with the above results, it was confirmed that the system properly controls each lighting fixture to various requirements from office workers.

4 Conclusion

It was discussed in this paper to achieve illuminance required by each office worker in the large-scale intelligent lighting system constructed in the actual office environment. The system operation was then verified based on the log data output for verification experiments. As a result of verification, it was confirmed that the system was successfully controlled in accordance with the target illuminance required by each office worker.

It is considered to be important to review illuminance favored by each office worker and verify long-term energy saving effects by analyzing the log data obtained through long-term operating experiments of the system in the future.

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