Optimization of Workers' Seat Layout and the Height of Height-Adjustable Luminaire for Intelligent Lighting System

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Abstract. We are doing reseaching and development of an intelligent lighting system to provide desired brightness to a desired place. In this study, we consider how to satisfy target illuminance for each worker and minimize power consumption with not only luminous intensity for each light but also the height of luminaire or workers' seating layout as the design variables. Therefore, highly-accurate target illuminance as well as very high illuminance can be realized and further energy saving is achieved.

Key words: lighting control, system, optimization, intellectual productivity, energy saving

1 Introduction

In recent years, intelligence has been incorporated in various systems including electric appliances and automobiles by autonomously controlling systems' own movements depending on the user or environment, leading to reduction of burdens on people. Intelligence relates to artifacts to make judgments based on their own knowledge obtained from sensors, etc. and take proper movements.

Intelligence for lighting systems was extremely low, although various systems have been acquiring intelligence. With common lighting systems in these days, the illumination pattern relies on power layout and switches, and such illumination pattern desired by a user may not be achieved in some cases. In addition, excessive brightness tends to be provided since there is no function to change the brightness of lights.

Under these circumstances, we are studying the intelligent lighting system to realize improvement of intellectual productivity as well as reduction of power consumption by providing brightness required individually (illuminance). As a result of basic experiments, this system is found to satisfy illuminance required by a worker and also realize high energy savings, and verification experiments are carried forward in the actual environment for practical application.

Since luminaires have a wide radiation angle in the case of current intelligent lighting systems, distribution of required illuminance might not be physically achieved in some cases, including the case that workers require significantly different levels of illuminance from each other or the case that illuminance beyond the capacity of luminaires is required. Therefore, a method to simultaneously satisfy various illuminance levels required by workers is proposed in this study by using height-adjustable luminaires, with not only luminous intensity for each light but also the luminaire height as the design variables. A method with workers' seating layout as the design variable is also proposed, and the effect is verified using simulation.

2 Intelligent lighting system

2.1 Components of intelligent lighting system

With the intelligent lighting system, multiple luminaires independently adjust the brightness of the lights (luminous intensity) to realize illuminance required by workers[1].

In the intelligent lighting system, multiple dimmable lights, the light control device attached, multiple movable illuminance sensors, and the electric meter are connected to one network. Since a distributed autonomous optimization algorithm is incorporated in the control device installed in each lighting equipment, it can operate as the distributed autonomous system as a whole. The composition of the intelligent lighting system is indicated in Fig.1.

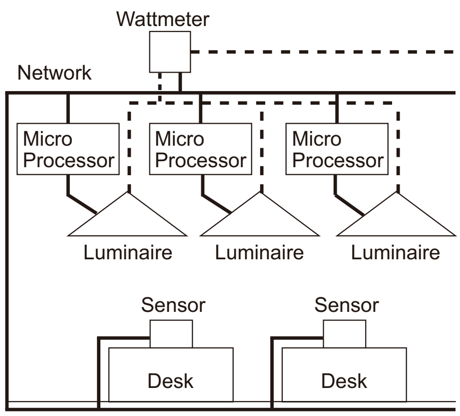

Fig. 1. Composition of the intelligent lighting system

2.2 Control algorithm for the intelligent lighting system

In the intelligent lighting system, each worker enters desired illuminance (target illuminance) in the system. The microprocessor built in each light controls its own luminous intensity by using the distributed autonomous algorithm. Adaptive Neighborhood Algorithm using Correlation Coefficient (ANA/CC) [4] is used as the optimization method.

ANA/CC is the improvement to control lights based on Simulated Annealing (SA). In SA, the subsequent solution is generated randomly around the current solution, and accepted based on the change in the objective function value as well as on the temperature parameter. It is the algorithm to obtain the (local) optimal solution by repeating this. In ANA/CC, the variation range of the design variable is changed instead of the temperature parameter, and the schematic mutual positions are kinetically learned in accordance with the correlation between the light and illuminance sensor. Based on the correlation, the design variable, i.e., the range to generate the next luminous intensity is adaptively determined. In ANA/CC, the correlation coefficient is calculated based on the change in luminous intensity as well as in illuminance for each light. The control flow for ANA/CC is described in the following:

1. Establish initial parameters including the initial luminous intensity.
2. Illuminate each light at the initial luminous intensity.
3. Obtain sensor information for each illuminance sensor (sensor ID, current illuminance and target illuminance) and power usage measured with an electric meter, based on which the objective function value is calculated.
4. Determine the proper range to generate the next luminous intensity based on the correlation coefficient.
5. Randomly generate the next luminous intensity within the range determined in Step 4 and illuminate the light at the luminous intensity.
6. Obtain sensor information for each illuminance sensor as well as the power usage with the electric meter again.
7. Calculate the correlation coefficient from the current illuminance obtained and the luminous intensity changed.
8. Calculate the objective function value under the illuminated condition with the changed luminous intensity, based on the sensor information and power usage.
9. If the objective function value turns good, confirm the luminous intensity and return to Step 3.
10. If the objective function value turns poor in Step 8, cancel the changed luminous intensity and return to Step 3.

Based on the above movement, the mutual location relationship between the light and illuminance sensor is understood using the correlation coefficient, to achieve the target illuminance with unwasted movement and at the same time promptly converge into the energy-saving mode. The reason to return to Step 3 rather than Step 4 in Steps 9 and 10 is to respond to kinetic changes in the environment such as shift of illuminance sensor and incoming radiation of outside light.

2.3 Achievement of target illuminance

It has already been confirmed that the intelligent lighting system is able to provide illuminance required by each worker and realize energy saving, while there are possible situations where distribution of desired illuminance cannot be physically achieved in some cases. For example, they include a case that adjacent workers require illuminance levels significantly different from each other, a case that some workers require very high illuminance, and a case that a worker requiring high illuminance is in the corner of a room.

In order to satisfy these types of lighting requirements which are difficult to achieve, it is necessary to make the height of luminaires adjustable or to change workers' seating layout. In this study, distribution of illuminance levels that could not have been realized in the past is realized, by making the height of luminaires adjustable vertically to the ceiling surface (height-adjustable luminaires) the design variable or by making workers' seating layout the design variable.

3 Optimization of the luminaire height to achieve personal illuminance

3.1 Control algorithm

As a method to satisfy the requirement mentioned in Section 2.3, we propose a method to achieve required illuminance that could not have been realized in the past with minimum energy, by using height-adjustable luminaires and making the height of each luminaire the design variable. The control algorithm is indicated in the following:

1. Fix the height of luminaires, optimize the luminous intensity for each light by using ANA/CC, and obtain the objective function value under this condition.
2. Randomly change the height of all luminaires.
3. Optimize the luminous intensity for each light under the condition that the height of luminaires is changed.
4. Obtain the objective function value again. If the value turns good, maintain the present height of luminaires. If the value turns poor, return to the height of luminaires before moving.
5. Repeat the operation in Steps 2 to 4, and end it when illuminance required by all workers is achieved or when processing is performed more than a certain number of times.

The objective function used in this algorithm is indicated in Eq.(1):

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

$$g_i = \begin{cases} (Lt_i - Lc_i)^2 & 50 \leq |Lt_i - Lc_i| \\ 0 & otherwise \end{cases}$$

P: power consumption, w: weight, Lc: current illuminance, Lt: target illuminance, n: number of illuminance sensors

The objective function consists of power consumption P and illuminance difference g_i, and priority of power consumption reduction over illuminance achievement is determined by changing the weight w. g_i is the value to be added when the difference between the target illuminance and the current illuminance is 50 lx or more, and the square of the difference is used.

3.2 Change of luminaire height

A method to determine the variation range of the height in regards to height-adjustable luminaires is discussed. As mentioned in Section 2.2, the location relationship between a light and illuminance sensor is schematically understood by obtaining the correlation coefficient based on the change in luminous intensity and illuminance for each light in ANA/CC. By setting the condition to the randomly changing height of luminaires in accordance with this schematic location relationship, the target illuminance seems to be satisfied with less number of search times, quickly converging into a state of minimum energy. The one-time variation range of the luminaire height is indicated in Fig.2.

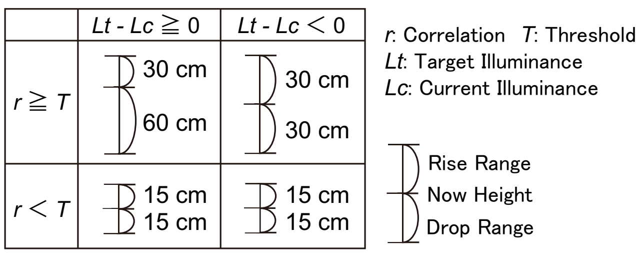

Fig. 2. One-time variation range of luminaire height

As indicated in Fig.2, illuminance is deficient even though the intended light influences the illuminance sensor, when the correlation coefficient between a light and illuminance sensor is more than the threshold and the current illuminance is lower than the target illuminance. In this case, higher illuminance is achieved by reducing the luminaire height. For this purpose, the downside of the variation range of the luminaire height is prioritized. On the contrary, the luminaire height is changed to even out the top and bottom, when the correlation coefficient is more than the threshold and the current illuminance is higher than the target illuminance. When the correlation coefficient is smaller than the threshold, the influence of the light is considered to be small; therefore the variation range of the luminaire height is narrowed to eliminate wasteful searching without relying on the values of current illuminance and target illuminance. By designing the one-time variation range of the luminaire height in this way, the luminaire becomes low in a place requiring illuminance and the illuminance required by a worker is achieved.

3.3 Evaluation experiment of the system

When extremely high illuminance levels are required The evaluation experiment is conducted by simulation in order to verify the effectiveness of the algorithm proposed. The criterion to determine convergence of illuminance is when the difference between the target illuminance and the current illuminance is within ± 50 lx. This is because people are not able to recognize the difference in illuminance at 50 lx level[5].

First of all, the verification experiment is conducted in the case that some workers require extremely high levels of illuminance. In this experiment, a situation where one out of three workers requires very high illuminance under the environment of 15 white fluorescent lamps is assumed. The results when only the luminous intensity for each light is optimized without changing the luminaire height are indicated in Fig.3-(a), and the results when the luminaire height is optimized from that situation are indicated in Fig.3-(b).

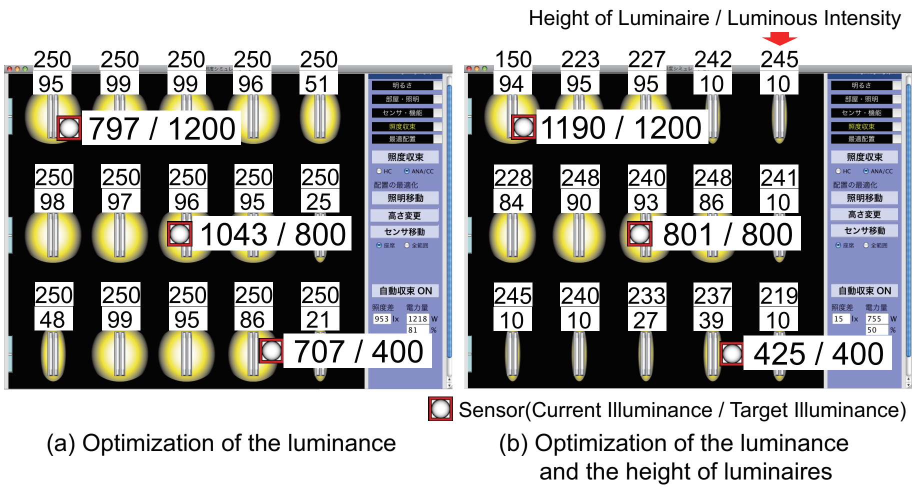

Fig. 3. The case that some workers require extremely high levels of illuminance

In Fig.3-(a), the luminaire height is not changed and high illuminance of 1200 lx is required in the upper left place. All lights illuminate at high luminous intensity in order to achieve the illuminance, but still the requirement of 1200 lx cannot be achieved. In regards to other places, the difference from the required illuminance increases.

On the other hand in Fig.3-(b), the 1200 lx requirement is achieved by optimizing the luminaire height, and the target illuminance is also achieved for all workers. The height of the luminaire closest to the worker requiring high illuminance is significantly reduced from the initial value of 250 cm to 150 cm. In this way, the maximum illuminance can be increased by lowering the luminaire height. Based on the above, making the luminaire height the design variable is effective in the case that some workers require high illuminance levels.

When adjacent workers require significantly different levels of illuminance A verification experiment in the case that adjacent workers require significantly different levels of illuminance is conducted under the condition of 15 white fluorescent lamps and six workers requiring different illuminance levels. Three low values (500, 540, 600 lx) and three high values (700, 760, 800 lx) of target illuminance are alternatively arranged. As a result of optimizing the luminous intensity for each light without changing the luminaire height under this situation, only three out of six workers' required illuminance is achieved and power consumption for the lights is 62 % of the time when all lights are illuminated at one hundred percent level, as indicated in Fig.4-(a). On the contrary, in the case of optimizing the luminous intensity for each light as well as the luminaire height, illuminance required by all workers is achieved and the power consumption for the light is 52 %, as indicated in Fig.4-(b).

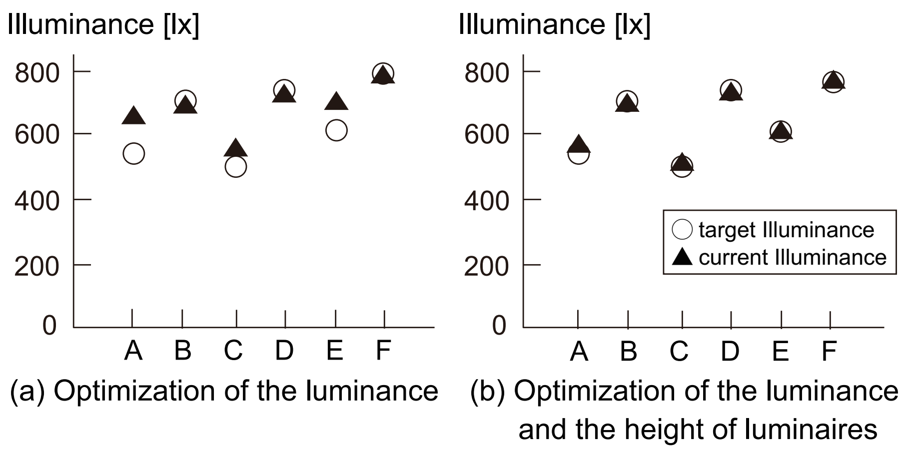

Fig. 4. Target illuminance and realization illuminance of workers

When the results of Fig.3-(a) and (b) are compared, it is found that illuminance required by workers can be achieved at high accuracy by optimizing the luminaire height. In this way, the target illuminance for all workers is also achieved in the case that adjacent workers require significantly different levels of illuminance, and more energy savings is achieved than in the case that the height is not made the design variable. In accordance with the above, making the luminaire height the design variable is effective to realize significantly different levels of illuminance that could not have been achieved before.

4 Optimization of workers' seating layout to precisely achieve personal illuminance

4.1 Control algorithm

By making not only luminous intensity for each light but also workers' seating layout the design variables as the method to satisfy the requirement mentioned in Section 2.3, a method to realize the required illuminance that could not have been realized before at minimum power consumption is proposed. The control algorithm is indicated in the following:

1. Optimize the luminous intensity for each light under the condition of fixed seating, and obtain the objective function value under this condition.
2. Randomly change the seating layout of all workers.
3. Optimize the luminous intensity for each light under this condition.
4. Obtain the objective function value again. If the objective function value turns good, maintain the seating layout. If it turns poor, return to the seating layout before the change.
5. Repeat the operation in Steps 2 to 4, and end it when illuminance for all workers is achieved or when processing is performed more than a certain number of times.

The objective function used for this algorithm is Eq.(1), like that used for optimization of the height of a light.

4.2 Evaluation experiment of the system

The verification experiment is conducted by simulation in order to verify the effectiveness of the algorithm proposed. The criterion to determine convergence of illuminance is when the current illuminance reaches within $\pm$ 50 lx of the target illuminance, as mentioned earlier.

This experiment is performed on the basis that nine people are seated in one room. Results between the case that workers are seated at random and the case that they are seated at the most suitable locations are compared. The illuminance levels required by workers are random values between 400 lx and 800 lx. Fig.5-(a) indicates the results of the case that workers are freely seated, and Fig.5-(b) indicates the results of the case that they are seated in accordance with the optimized seating layout. Fig.6 indicates the target illuminance and current illuminance for nine people.

When workers are freely seated as indicated in Fig.5-(a), the illuminance required by only four out of nine workers is achieved as indicated in Fig.6-(a),

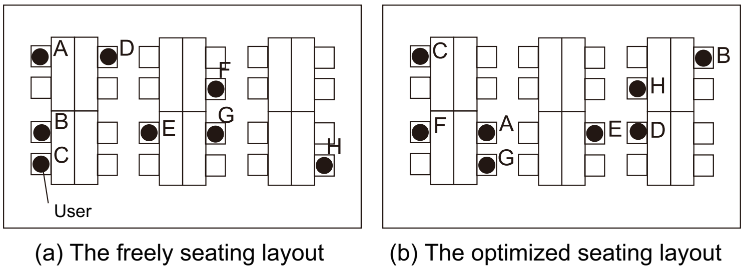

Fig. 5. freely seating layout and optimized seating layout

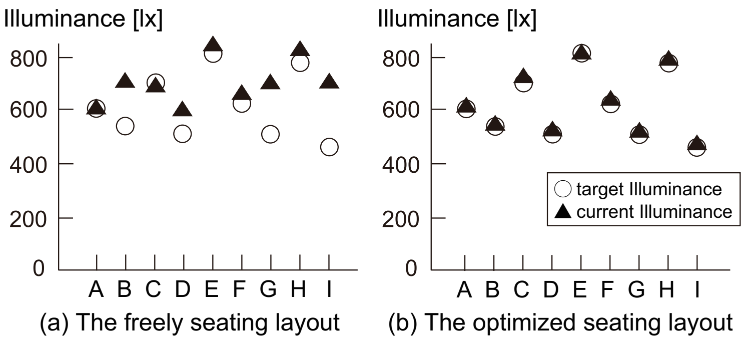

Fig. 6. Target illuminance and realization illuminance of workers

and the power consumption for the lights is 70 % of the time when all lights are illuminated at one hundred percent level. On the other hand, in the case of Fig.5-(b) where they are seated at the optimized locations, the illuminance required by all workers is achieved as indicated in Fig.6-(b), and the power consumption for the lights is 56 %.

5 Conclusion

In this study, a method is proposed to realize the required illuminance by optimizing not only the luminous intensity but also the height by using height-adjustable luminaires, in the case that distribution of desirable illuminance levels cannot be physically achieved, including the case that adjacent workers require significantly different levels of illuminance from each other. It is found that this method has the effect to increase the maximum illuminance which could not have been achieved before, as well as the effect to satisfy different levels of illuminance which could also not have been achieved before.

In addition, a method to realize distribution of luminance levels that cannot be achieved by fixed seating is proposed by optimizing workers' seating layout without changing the luminaire height. It is found that this method is effective in achieving workers' required illuminance more accurately than before and also in achieving further energy savings.

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