座席配置の最適化に基づくインテリジェントな照明制御方法

Seat Optimization-Based Intelligent Lighting Control

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要　旨

現在では，照明制御技術によって明るさと消費電力を両立させて制御することが可能となってきている．ただし，このような技術によって明るさに対する要求を満たすことはできるようになっているが，より快適なオフィス環境を実現するためには明るさ以外の要求を考慮する必要がある．我々は，PSO (Particle Swarm Optimization) に基づき座席配置と照明制御とを組み合わせたシステムを提案する．ここでは，座席の位置，座る人の間の社会的関係性および明るさに対する要求を取り上げ，PSO手法を用いて座席配置と明るさを最適化する．シミュレーションの結果，この手法を用いるとランダムに着席する場合と比較して快適性が77%から96%まで向上した．必要な照度は33 lxから19 lxまで低減でき，この結果消費電力も149.5 W/hから126.6 W/hに減少した．これにより我々の手法の実効性・有効性を確認することができた．

ABSTRACT

At the present time, lighting system controls are primarily used for lighting and energy efficiency, but this merely meets the user preference for illuminance requirements. To further improve the general comfort of users in the office environment, other preferences and requirements need to be considered. In this paper, a PSO (particle swarm optimization) -based method combining seats and lights is proposed. The requirements for seat position, social relationship, and lighting are met by iteratively optimizing seat assignment and dimming the level of lighting in the PSO framework. In a simulation, our proposed PSO method outperforms randomly selecting seats. The general comfort degree was improved from 77% to 96%, mean illuminance error was reduced from 33 lx to 19 lx, and the power consumption decreased from 149.5 W/h to 126.6 W/h. The simulation results verify that our method is both feasible and effective.

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1. Introduction

With the recent advances in communications, control, and lighting product development, electric lighting systems with automatic dimming for energy conservation and user comfort enhancement have been receiving widespread attention. Previous publications have elaborated on the concept of prototypical implementations of intelligent lighting control[1-4]. The research results[4] indicate that the energy consumption of these systems is 42-47% lower than that of conventional systems. Meanwhile, people are paying more and more attention to the improvement of user comfort. It has been widely acknowledged that individual users have diverse illuminance preferences for different activities, and these may vary significantly from person to person[5-7]. Typically, the trade-off between meeting user preferences for indoor environmental conditions and reduction in energy usage leads to a difficult optimization problem. Several works[1,2,8] have investigated the lighting problem of improving user comfort and reducing energy costs. One work[1] uses several kinds of illuminance constraints to meet user requirements. In it, the users' needs were met by adjusting background illuminations near lighted task areas. Another work[2] defines personalized comfort by using different numerical values to indicate desired illuminance values and minimizes the illuminance error of all users. Yet another work[8] presents user preferences as having a utility function relating to the users' position and lighting devices.

Until now, most literature[1-3,8] provides a lighting control solution to fixed seats in accordance with a personalized illuminance preference. However, this is not always effective. For example, if a crowd with large differences in preferences sits in an adjacent area these lighting preferences would be counterproductive. To optimize lighting control for non-fixed seats, optimizing the users' seating layout by reducing the illuminance error of users' preferences, thus improving the illuminance preference has been proposed[9]. However, in real-world settings, the user's comfort limits the illuminance preference as it is affected by social relationships and location preference[10]. Therefore, seat optimization based on multiple preferences has more practical value in an actual environment.

Multiple preferences in comfort enhancement can be studied as a multi-object optimization problem. They are difficult to solve by traditional linear or nonlinear methods, but evolutionary computation techniques, such as genetic algorithm (GA), ant colony search algorithm (ACSA), and particle swarm optimization (PSO), can be used in seat optimization since an exhaustive search is impractical. PSO was formulated by Eberhart and Kennedy[11] in 1995 and improved by Shi and Eberhart[12]. The thought process behind the algorithm was inspired by the working behavior of animals, such as birds flocking or fish schooling. Preference-based seat optimization can use the idea of PSO since people with similar preferences tend to come together. In addition, unlike the GA, PSO has no evolutionary operators such as crossover and mutation, so there are few parameters that need to be adjusted. Furthermore, it is easy to implement on hardware or software[13]. Based on the above considerations, a PSO method was developed to address the problem of preference-based seat optimization.

This solution is devoted to enhancing the users' comfort and energy efficiency while taking into consideration their position preferences, illuminance preferences, and social relationship preferences.

2. Lighting control system overview

2-1 Introduction to intelligent lighting control system

The intelligent lighting control system is shown in Fig. 1. The intelligent lighting control system is configured with dimmable lamps, user ID recognition sensors, and illuminance sensors connected to a wireless base station. The whole system includes two modules: the main PSO-based seat assignment module and the built-in lighting control module in the PSO algorithm. In addition, there are two databases. One is a user preference database that stores user position preferences, illuminance preferences, and social relationships. The other is a lamp characteristics database that stores the lamp's illuminance value at given levels for all seat positions. Based on these two databases and the illuminance conditions in the regions of assigned seats, the system will recommend a solution of optimal dimming signals of lamps and seat numbers for users.

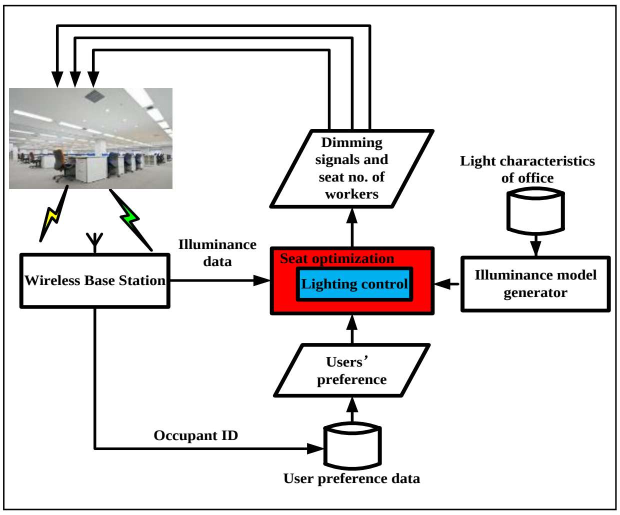

Fig. 1 Concept of seat optimization-based intelligent lighting control.

2-2 Intelligent lighting control system process

The intelligent lighting system is controlled by using the PSO method, which improves user comfort by properly assigning seats. Illuminance error is reduced by globally considering the users' illuminance preferences. The control process is described below:

Step 1: Obtain the user's preferences from the preference database by recognizing the user ID.

Step 2: Randomly generate n seat assignment solutions.

Step 3: Based on the assigned seats, adjust the dimming level of lamps through minimizing the electric power and the error between the target illuminance and real illuminance.

Step 4: Select the best seat solution by evaluating the satisfaction degree (SD) of the seat assignment, illuminance error, and power consumption.

Step 5: Move the current seat assignment solutions toward the best solution.

Step 6: Repeat step 3 to 5 until the evaluation meets the requirement or the process has been performed more than a certain number of iterations.

3. Seat optimization-based lighting control algorithm

3-1 PSO-based seat optimization algorithm introduction

In seats assignments, each particle contains a vector of seat numbers that presents a feasible solution of seat assignments. The seat assignments are updated based on the local and global best solutions. A potential solution is represented by a particle that adjusts its position and velocity in accordance with equation (1) and (2):

$$V_{id}^{t+1} = \omega V_{id}^{t} + c_1 \times r_1 (p_{id}^{localBest} - x_{id}^{t}) + c_2 \times r_2 (p_{id}^{globalBest} - x_{id}^{t}) \qquad (1)$$

$$x_{id}^{t+1} = x_{id}^{t} + V_{id}^{t+1} \qquad (2)$$

Where t is the iteration index, i is the index of the seat assignment solution, d is the dimension index such as the number of users waiting for seat assignments, V^t is the moving step size of the seat number in one seat solution, and x^t is the position of one seat assignment solution at time t. $p_{id}^{localBest}$ is the best position solution in the current iteration. $p_{id}^{globalBest}$ is the established global best position solution. r_1 and r_2 are independent uniform random numbers, and c_1 and c_2 are learning factors. ω is the inertia weight.

3-2 Utility function construction

To apply PSO to a multi-objective seat optimization problem, the multiple objectives are normally weighted and combined to form a single objective. The single fitness function can then be formulated as:

$$\max U = \frac{1}{N}\sum_{i=1}^{N}[\alpha_{1i}S^{(P)}(x_i)+\alpha_{2i}S^{(R)}(x_i)] - \beta MIER - \eta MPCR \quad (3)$$
$$\alpha_{1i}+\alpha_{2i}=1, i=1,\ldots,N$$

where *i* is the user index and equals 1,…,N, and x_i is the assigned seat for person *i*. $S^{(P)}$ is the position SD. $S^{(R)}$ is the social relationship SD. *MIER* is the mean of illuminance error ratio. *MPCR* is the Mean of Power Consumption Ratio. α_{1i} and α_{2i} are the weights of position preference and social relationship preference for user *i*, respectively. β and η are the weights of illuminance error and power consumption, respectively.

In Eq. (3), the utility function includes three terms. The first is the comfort term, which is based on the evaluation of position and social relationship preference. The second is the evaluation of illuminance error of users. The third is the total power consumption of lighting.

3-2-1 Representation of SD of position

To model $S^{(P)}(x_i)$, two methods were used to obtain the SD of a seat:

- Using questionnaires to collect SD scores of user position preferences such as window preference, corner preference, and middle preference.
- Using descending position scores to assign a value automatically if users do not indicate one.

For example, for a seat that is far away from windows, the SD of window preference will be lower than the SDs for seats near windows.

3-2-2 Representation of SD of social relationship

To model $S^{(R)}(x_i)$, social relationship information needs to be collected, including information such as user *A* likes user *B* and user *A* dislikes user *C*. Then, a distance dependent function is constructed for representing the SD of social relationships as shown in Fig. 2. The representation of social relationship SD is described as:

$$S^{(R)}(x_i) = \frac{\sum^{N_1} T_j + \rho\sum^{N_2} T_j}{N_1 + N_2} \quad (4)$$

where N_1 and N_2 are the people user *i* likes and dislikes in the range of circle (r <= r1) and (r1 < r <= r2), respectively. ρ (0 < ρ < 1) is the weight of SD score in the circle (r1 < r <= r2). T_j is 1/-1 if user *i* likes/dislikes the person in the corresponding *j* index.

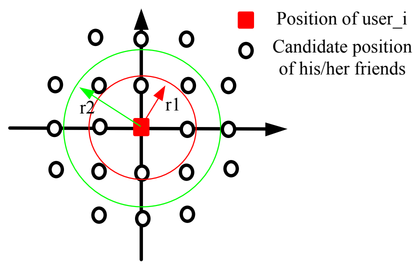

Fig. 2 Diagram of social relationship with distance.

3-2-3 Representation of SD of illuminance error and power consumption

In this part, $\overline{E}_i$ is the target illuminance of user *i*, and *i* = 1,…,*N*, which is the measured illuminance of user *i* after the dimming adjustment. The illuminance error is formulated by *MIER*, which can be described as:

$$MIER = \frac{1}{N}\sum_{i=1}^{N}\left|\frac{\overline{E}_i - E_i}{\overline{E}_i}\right| \quad (5)$$

The power consumption can be formulated by *MPCR*, which is described as:

$$MPCR = \frac{\sum_{i=1}^{M} P_i(D_i+\Delta_i)}{\sum_{i=1}^{M} P_i} \quad (6)$$

where P_i is the nominal power of the lamp *i*, and *i* = 1,…,M. D_i and Δ_i are the current dimming level and optimal adjustment of lamp *i*, respectively. The solution of optimal Δ_i for each lamp will be described in Section 3-4.

The illuminance error term *MIRE* and power consumption term *MPCR* can be converted to the terms of utility function by:

$$U' = -MIRE - MPCR \quad (7)$$

Maximizing the utility term U' will reduce the illuminance error of the users and power consumption of electricity. Finally, the overall evaluation of the system is formulated in Equation 3.

3-3 Conflict avoidance in seat assignments

During a swarm, particles move toward the best historical position. Since each particle contains a vector of assigned seat numbers, the seat numbers are adjusted toward the historical best position. It is possible that there are overlapping seat assignments for two or more persons in an assignment solution after moving. This problem is shown in Figure 3.

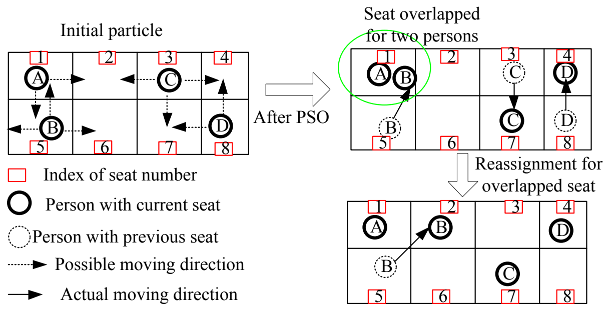

Fig. 3 Diagram of overlapping seat assignments.

To solve this problem, we built a discrete set of seat scores for position preference and used a roulette wheel mechanism to probabilistically assign a seat for the overlapped persons. On the other hand, when the overlapped person emphasizes social relationship, a strategy to find the seat number of his friend and assign a seat nearby is implemented. A detailed flow chart is shown in Fig. 4. By using this method, the users with overlapped seat assignments will effectively get a unique seat with a higher satisfaction degree.

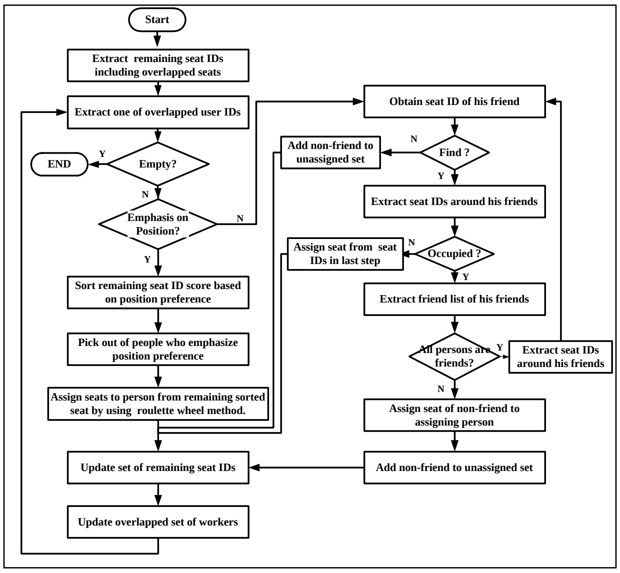

Fig. 4 Flow chart of seat reassignment.

3-4 User lighting optimization

After an optimal seat assignment is given, the lighting at the user's position will be determined. One study[14)] described a detailed design process for the optimization of lamps' dimming level. Since we only sought to obtain the final status of lighting in this paper, a modified objective of lighting control in the study[14)] is formulated as:

$$\min J = [E^{(t)} + K\Delta - \overline{E}]^T [E^{(t)} + K\Delta - \overline{E}] + \mu \| D + \Delta \|^2$$

$$S.T.\ \ 0 \le D_i + \Delta_i \le 1, \quad i = 1,2,\ldots,m$$

where $E^{(t)}$ is the illuminance vector before adjustment, K is the lighting effect matrix at the assigned seat position, and μ is the weight of power consumption. D_i and Δ_i are the current dimming level and adjustment of lamp i, respectively.

4. Simulation and result analysis

The office model shown in Fig. 5 is constructed using the DIALux lighting simulation software. The layout of the office is 15 x 14 x 2.8 m (L x W x H). In this simulation, we assume that the system has already obtained six position preferences and social relationship preferences, as shown in Tables 1 and 2. In Table 2, the values of 1, -1, and 0 indicate like, dislike, and no preference. For example, from Table 2 we can see that user_1 dislikes user_2, and user_2 dislikes user_1. The comfort weight between the position and social relationship for all users are shown in Table 3. The initial plan shown in Fig. 6 is a randomized seat assignment in which lighting is optimized. Since user_1 and user_2 have a bad relationship, the initial seat assignment solution reduces the comfort value, both universally and for the individuals, when user_1 and user_2 are seated beside each other. Fig. 7 and 8 show a better performance result and PSO implementation, respectively.

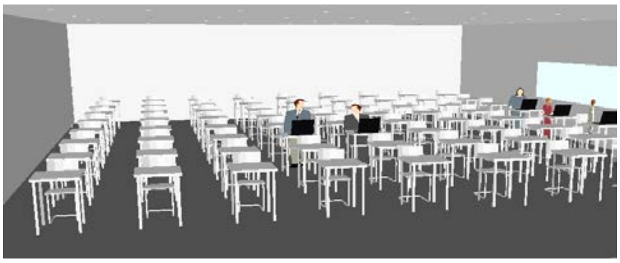

Fig. 5　Overview of office model.

Table 1　Position preferences of users.

	Position preference
User1	Window
User2	Window
User3	Window
User4	Corner
User5	Corner
User6	Middle

Table 2　Social relationship preferences of users.

	User1	User2	User3	User4	User5	User6
User1	0	-1	1	0	0	0
User2	-1	0	1	0	0	0
User3	1	1	0	0	0	0
User4	0	0	0	0	1	0
User5	0	0	0	1	0	0
User6	0	0	0	0	0	0

Table 3　Weights between position preference and social relationship.

Weights	For position	For social relationship
W1	0.7	0.3
W2	0.4	0.6
W3	0.2	0.8
W4	0.7	0.3
W5	0.4	0.6
W6	1	0

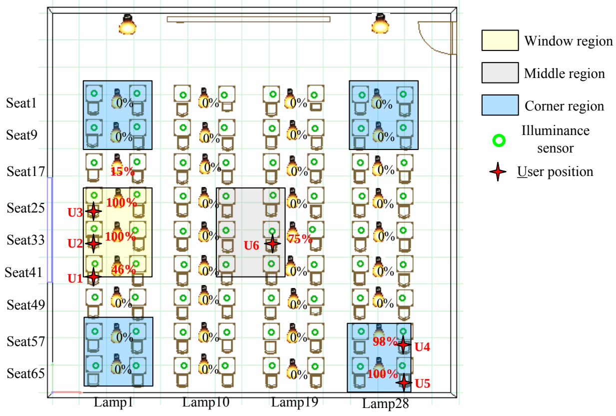

Fig. 6　Initial seats and lighting result without optimization.

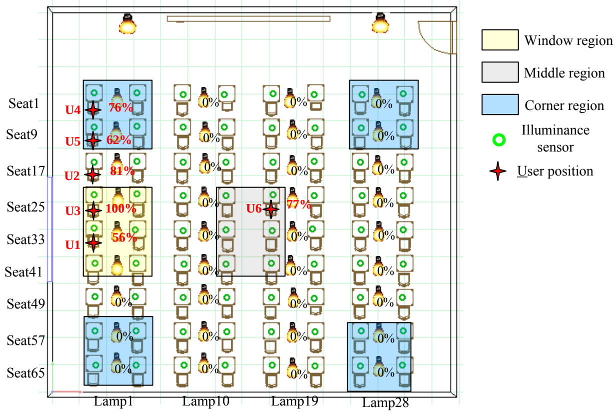

Fig. 7　Seat assignment and lighting results by PSO.

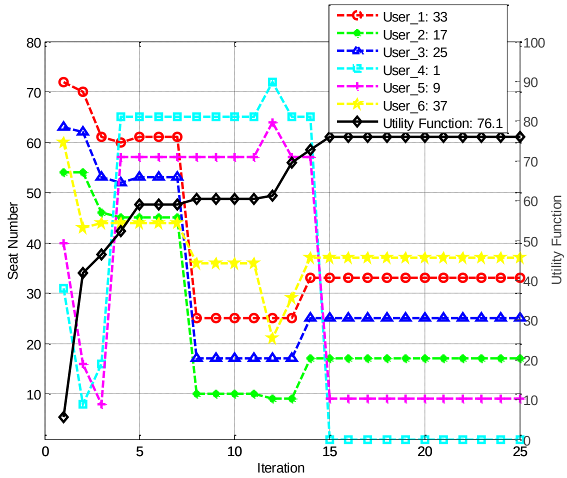

Fig. 8　Iteration results of PSO method.

Figure 9 shows the comfort evaluation of position preference SD and social relationship preference SD. We can see that the overall comfort is improved.

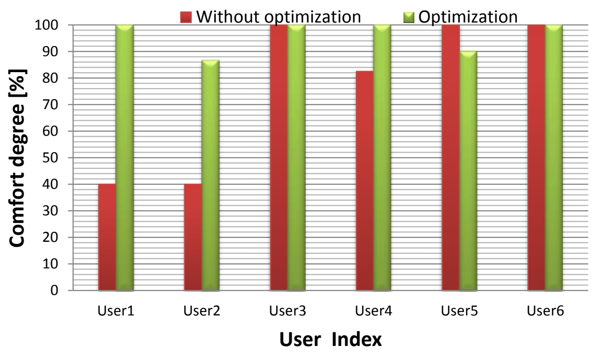

Fig. 9　Comparison of comfort results.

Illuminance results of all users are shown in Fig. 10. We can see the illuminance error is reduced through system optimization.

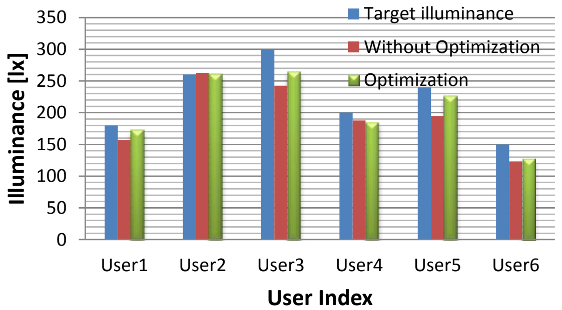

Fig. 10 Comparison of illuminance result.

Fig. 11 shows the power consumption of the two solutions. We can see the power consumption is remarkably reduced by using the PSO method.

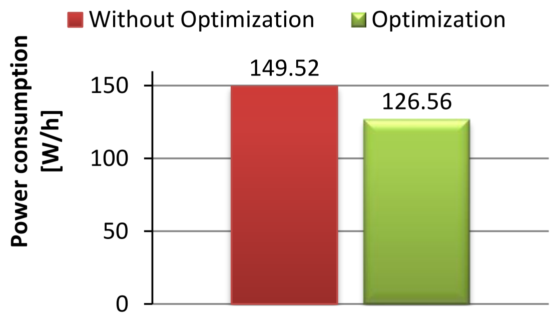

Fig. 11 Comparison of power consumption results.

From Fig. 9, further analysis verifies that the overall comfort degree is improved from 77% to 96%. Before optimization, user_1 and user_2 disliked each other, causing their own and overall comfort values to be low. After PSO, their comfort values improved. For user_5, the reduced comfort value came mainly from changing the position score. Since user_5 emphasizes the relationship preference over physical position preference, the system makes a trade-off between the comfort value and illuminance error optimization using Equation 3. We can see that the illuminance error of user_5 is reduced after user_2's and user_5's seats are moved closer together. The main reason is that the desired illuminance between user_2 and user_5 is similar, as shown in Fig. 10, meaning user_5 shares the illuminance preference of user_2. After further calculation, the total mean illuminance error is reduced from 33 lx to 19 lx, and the power consumption is reduced from 149.5 W/h to 126.6 W/h, as shown in Fig. 11.

5. Conclusion and future work

5-1 Conclusion

We have presented an intelligent lighting control system to improve user comfort while also reducing energy consumption. Using this method, the overall comfort was improved by assigning seats with global considerations and in such a way that electricity is used more efficiently by pre-optimizing lighting parameters. The simulation results verified our algorithm. Generally speaking, our algorithm has the ability to improve conflicts between comfort, illuminance error, and power consumption by controlling parameters β and η in Equation 3. By using this technique, other more complex and actual problems can be addressed for business applications.

5-2 Future works

Our next step is to build a real experimental environment with illuminance sensors and a preference collection system to verify the PSO-based lighting control algorithm.

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