

Intelligent Lighting Control User Interface through Design of Illuminance Distribution

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Abstract—Many types of artifacts can be connected and controlled over a network. However, when a lot of artifacts are connected, it is very difficult to control with conventional interface switches. The interface of these systems should be suitable for each individual user and should be designed for ease of operation. In this paper, a new type of user-friendly interface for a networked lighting system that can be controlled over the network is proposed. In the proposed system, the user operates the lighting system by designing the illuminance distribution, and the system learns user's sensory scale to support this design.

Keywords—user interface; lighting; illuminance distribution; network;

I. INTRODUCTION

As technology is becoming increasingly ubiquitous, we are surrounded more frequently by many types of hardware, such as computers and sensors, which are connected to networks[1][2]. Networking such equipment can improve the function of the system. However, as the functionality of the system improves, user operation will become more complex and diverse, increasing the burden on the users. Therefore, it is necessary to improve the usability of the user interface (UI) of such networked systems.

The operation burden for lighting systems will increase as they are connected to a network. Lighting systems have advanced such that it is now possible to control of multiple lighting systems individually by networking[3]. However, the operation of such lighting systems has also become complex. Consequently, traditional UI for such system will create a large burden for user operation. In this paper, the requirements of a UI that is suitable for hardware networking will be described, and an example of a UI for networked lighting system that learns user's sensory scale and allows lighting control through the design of illuminance

distribution is proposed.

II. REQUIREMENTS OF THE UI IN NETWORKING

The UI for such a system in which different equipment is connected through a network has two requirements: intuitive operability and personalization features[4][5]. The former requirement is necessary because if the user can intuitively understand the method to obtain a desired result, the burden of operation will be reduced. The latter requirement is necessary because if the method of operation is optimized for each user using the preferred display or frequency of use, the UI will become easier to use.

Thus, it is important to facilitate the users reaching their desired results through the UI. A UI should be designed taking this concept into consideration while connecting hardware through the network.

III. UI IN NETWORKED LIGHTING SYSTEM

A. Networking the Lighting Equipment

In the past, lighting systems controlled multiple lights at once, and all that was needed as a UI was a switch to turn the lights ON or OFF. On the other hand, in the current lighting system, the lights and control devices that can control the luminance of individual lights are connected to the network, allowing multiple lights to be controlled individually[3]. In this study, we constructed a laboratory equipped with such a lighting system, as shown in Fig. 1.

All of the 48 lights in the laboratory shown in Fig. 1 can be controlled individually. An overview of the lighting system network in this laboratory is shown in Fig. 2.

As shown in Fig. 2, each control device is connected to multiple lights, and can regulate up to 5 lights individually. By connecting multiple lights and their control devices to the network, individual control of multiple lights can be



Fig. 1. Laboratory Equipped with a Networked Lighting System

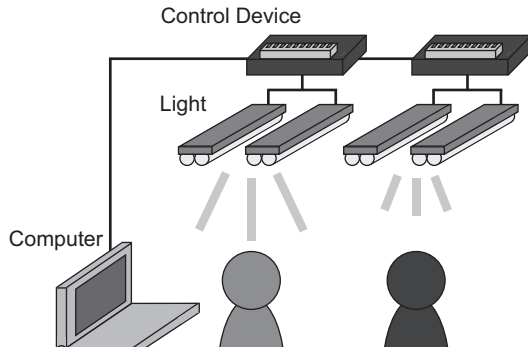


Fig. 2. Overview of the Lighting System Network in this Laboratory

achieved through a computer. This function allows a diverse lighting environment as well as offering different level of brightness to individuals in the same room.

However, as mentioned in Chapter 2, user operation becomes complex in this lighting system because the number of items that must be operated has increased. For such lighting systems, a UI that sets the luminance of lights individually has been suggested[6][7], but the operation of adjusting the luminance of individual lights separately is a large burden for the user. Therefore, a lighting control UI equipped with intuitive operability and the personalization features described in Chapter 2 was examined in this study.

B. Intuitive Operation

In a UI to allow intuitive operation of a lighting system, the most important factor is the operational object of the UI. The expected result of the system is the illuminance distribution, i.e., the brightness around the user. On the other hand, existing UI control lighting by regulating the luminance, which is the brightness emitted by the lights. Therefore, the user must estimate what luminance setting

will give the desired illuminance distribution. Therefore, it is more intuitive for the user to operate the illuminance distribution rather than to operate luminous intensity to obtain the desired illuminance distribution. Here, we set the illuminance distribution as the operational object in the proposal interface. Illuminance control at a given location has already been realized by utilizing a networked lighting system[8][9]. By incorporating an illuminance sensor into a network, this system can provide arbitrary illuminance at an arbitrary location based on information obtained from the sensor.

In the proposed UI, the illuminance distribution is visualized by 3-dimensional computer graphics (3DCG) to allow the user to understand the illuminance distribution easily. In addition, to make the operation more intuitive, the illuminance distribution design is realized through drag and drop.

C. Personalization Features

As described in Paragraph 3.2, the user designs the illuminance distribution through the UI to obtain a desired illuminance distribution. However, as the sensory scale to brightness differs for each user, there is a difference between the desired illuminance and that offered by the system, as shown in Fig. 3[10].

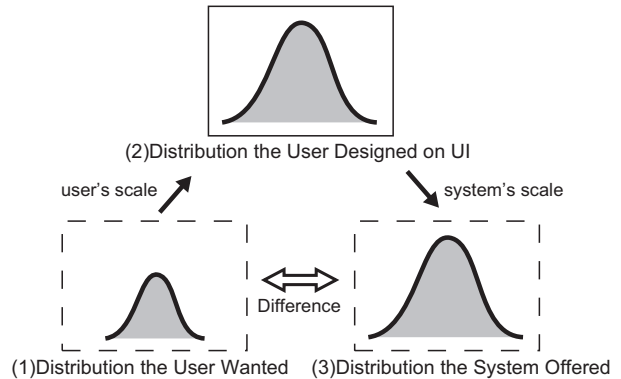


Fig. 3. Differences in Scales

As shown in Fig. 3, there is a difference between Fig. 3(1) Distribution the user wanted and Fig. 3(3) Distribution the system offered due to the difference in scales. Therefore, the user must learn what type of distribution should be designed on the UI to obtain the desired distribution. To reduce this burden, the system should personalize the scales for each user so that the system can offer the appropriate distribution in response to the user's design parameters. Consequently, the proposed UI is equipped with the ability to learn the sensory scales for brightness perceived by the user [11][12].

IV. INTELLIGENT LIGHTING CONTROL UI THROUGH ILLUMINANCE DISTRIBUTION DESIGN

In this paper, a UI that improves the usability of the networked lighting system is proposed. The requirements for improving the usability are shown below.

- **Designing the Illuminance Distribution**
The illuminance distribution, which is the result wanted by a user, is set as the operational object to realize intuitive operability. And, the system is equipped with the drag and drop operation which allows the users to design the illuminance distribution expressed by 3DCG more sensuously.
- **Controlling the Illuminance Distribution**
To set the illuminance distribution as the operational object, the system must control the illuminance distribution. Therefore, the system controls the illuminance distribution by simulating the illuminance obtained from the luminance.
- **Learning of the Sensory Scale**
Although the user designs the illuminance distribution by drag and drop operation, the sensory scale for brightness differs for each user. Consequently, the system can learn sensory scale of users.

A. Designing the Illuminance Distribution

The initial state of the proposed UI expressing the illuminance distribution by 3DCG is shown in Fig. 4.

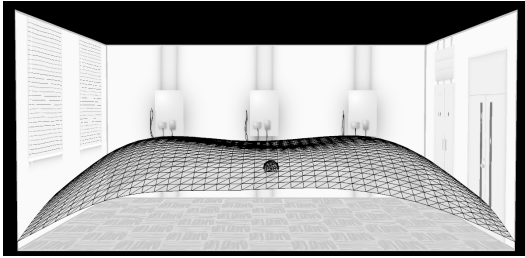


Fig. 4. Initial State of the Proposed UI

The UI in Fig. 4 models the laboratory introduced in Fig. 1. The mesh-like object at the center of Fig. 4 (referred to hereafter as the illuminance distribution object) expresses the indoor illuminance distribution using 3DCG, and is the user's operational object to adjust lighting; the closer a point on this object approaches the ceiling, the higher the illuminance becomes at that point in the room. When we set the two axes of the floor surface of the laboratory as the x- and y-axes, and the axis perpendicular to the floor surface as the z-axis, the coordinates of x and y indicate the position of this illuminance distribution object on the floor surface, and the z-axis indicates the illuminance at that position; the higher the number on the z-axis, the brighter the illuminance. The sphere on the illuminance distribution

object is the object that maps the position of a mouse pointer in 3D space, and is used as the reference point for drag and drop operation.

The proposed UI displays the feasible illuminance distribution, which is the result of simulation. Fig. 4 shows the illuminance distribution simulated such that illuminance in the room is kept as uniform as possible. In this UI, the user changes the shape of the illuminance distribution object by dragging and dropping at an arbitrary point on the object. This drag and drop operation can be performed in two directions; vertical and horizontal. When the drag and drop operation is performed in the vertical direction, a concavity/convexity is created, the depth/height of which is determined by where the user drops. When the drag and drop operation is performed in the horizontal direction, the concavity or convexity is widened or narrowed horizontally, and the width is determined by where the user drops. The illuminance distribution object, which was designed arbitrarily from the initial state in Fig. 4, is shown in Fig. 5.

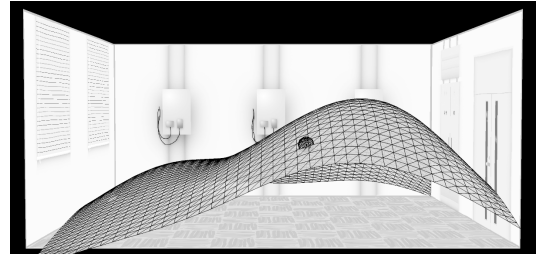


Fig. 5. The Proposed UI after Design

The state in Fig. 5 indicates that the system sets up the luminance of lighting so that the left side of the room becomes dark and the right side becomes bright.

B. Controlling the Illuminance Distribution

In the proposed UI, It is necessary to compute the luminance of each light to realize the illuminance distribution required by the user. Thus, the system realizes illuminance distribution control by simulating the illuminance distribution using the point-by-point method, which theoretically calculates the illuminance from the luminance [13][14]. The horizontal illuminance Eh calculated by the point-by-point method is shown in (1).

$$Eh = \frac{h}{\sqrt{h^2 + d^2}} \cdot En \quad (1)$$

$$En = \frac{l\theta}{2} \left(\frac{m}{h^2 + d^2 + m^2} + \frac{1}{\sqrt{h^2 + d^2}} \tan^{-1} \left(\frac{m}{\sqrt{h^2 + d^2}} \right) \right)$$

E_n : normal illuminance
 $l\theta$: θ directional luminance per unit measurement
 m : measurement of lighting

h : height of lighting
 d : horizontal distance between light under lighting
and measuring point

Eh obtained in (1) indicates the illuminance at a certain measurement point by a certain light. When there are a number of lights, the illuminance of a certain measured point is expressed by the summation of the illuminance given by each light. The illuminance Eh depends on the luminance $l\theta$, because m , h , and d in (1) are the constants that are uniquely set when the light and measurement point to simulate are determined. This illuminance distribution control is considered an optimization problem that calculates the luminances that minimize the difference between the illuminance distribution submitted by the user and that simulated by the point-by-point method. The object function f is formulated as (2).

$$\min \quad f(L\theta) = \sum_{i=1}^n (Eh_i(L\theta) - Eh_i^0)^2 \quad (2)$$

subject to $L\theta = \{ l\theta \mid 0 < l\theta < \text{maximum luminance} \}$

Eh_i^0 : target illuminance
 $L\theta$: a set of the luminance in all lightings
 $l\theta$: the luminance of certain lightings
 n : number of measurement point

$Eh_i(L\theta)$ in (2) is the illuminance of the measurement point i by the luminances of all lights. Eh_i^0 is the target illuminance of the measurement point i . As shown in (2), the object function is expressed by the summation of the square of the difference between the illuminance determined by simulation and the target illuminance, and the luminance that minimizes the evaluation value of the object function is the optimal solution. This object function is solved by the method of steepest descent, because it is a monomodality function[15][16].

The flow chart of illuminance distribution control using the method of steepest descent is shown in Fig. 6.

As shown in Fig. 6, the method of steepest descent is a technique for searching the minimum in the object function based on the gradient information on that function.

C. Learning the Sensory Scale

As described in Section 3.3, the proposed UI learns the sensory scale of brightness for each user because it differs between users [10][11][12]. The learning function was formulated supposing the situation were only one user has the discretion of the brightness of the room. To perform this learning, the system updates its own scale so that the peak in Fig. 3(1) and the peak in Fig. 3(3) match. This system has a two-dimensional array E as its scale. E_{ij} , which is the peak illuminance of the concavity or convexity

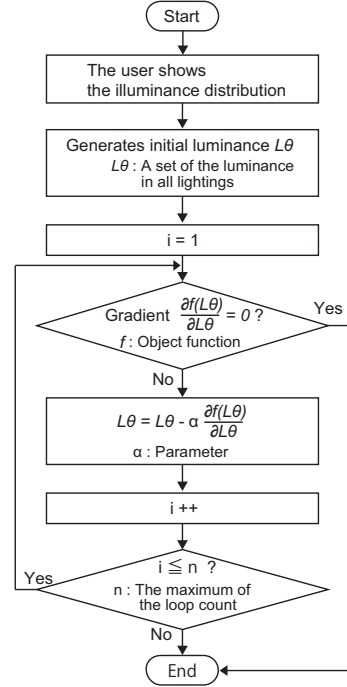


Fig. 6. Flow Chart of Illuminance Distribution Control

formed by the user dragging the cursor from the drag start point i for a drag distance j , is stored in the array E . The scale is set for every drag start illuminance because even if the user drags the same distance, the quantity of change required may differ depending on the starting illuminance. The flow chart of the learning mechanism of the proposed UI is shown in Fig. 7.

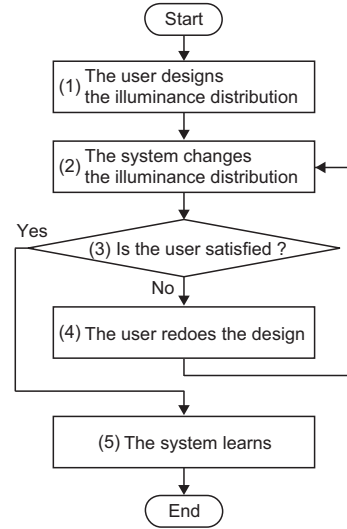


Fig. 7. Flow Chart of the Learning Mechanism

The mechanism of the learning in Fig. 7(5) is described

below. E_{ij} is defined as the peak illuminance of the illuminance distribution which the system offered first to the user in Fig. 7(2). e is defined as the peak illuminance of what the system offered last in Fig. 7(2). At this time, the top illuminance E_{ij} is updated according to (3).

$$E_{ij} = |e - E_{ij}| \cdot \alpha + E_{ij} \quad (3)$$

α : learning rate

α is a constant, and fulfills $0 \leq \alpha \leq 1$. To increase the learning speed, this system transmits this update into the two-dimensional array. Initially, the update propagation is transmitted into the sequence of the drag start illuminance i in the two-dimensional array. This updating is expressed as (4).

$$E_{n \ j} = |e - E_{ij}| \cdot \beta^{|i-n|} + E_{n \ j} \quad (4)$$

β : propagation rate on illuminance begun drag
 n : $0 \rightarrow i_{max}$ except i

β is the constant, and fulfills $0 \leq \beta \leq 1$. Next, the update propagation is transmitted into the sequence of the drag distance j in the two-dimensional array. This update is expressed as (5).

$$E_{n \ m} = |E_{n \ j} - E'_{n \ j}| \cdot \gamma^{|j-m|} + E_{n \ m} \quad (5)$$

$E'_{n \ j}$: illuminance before update
 γ : propagation rate on dragging distance
 n : $0 \rightarrow i_{max}$
 m : $0 \rightarrow j_{max}$ except j

γ is a constant, and fulfills $0 \leq \gamma \leq 1$. As this system learns the user's sensory scales, the user learns the scales of the system. Therefore, the system has the learning rate and the propagation rate to prevent the conflict between user learning and system learning.

V. NUMERICAL EXPERIMENT

This chapter describes the results of the numerical experiment regarding the illuminance distribution control algorithm and the learning function described in Chapter 4.

A. Numerical Experiment Results of the Illuminance Distribution Control Algorithm

This experiment was conducted assuming the laboratory shown in Fig. 1. However, the 48 lights in this laboratory consisted of 24 pairs of lights, and thus one pair of lights was considered as one light in this experiment. This luminance $l\theta$ is $0 \leq l\theta \leq 3633$. This laboratory measured $8.26m * 6.15m$, with a height of $2.75m$. The number of the illuminance measurement points was set to 1681. Under these conditions, the object function of (2) was optimized based on the flow

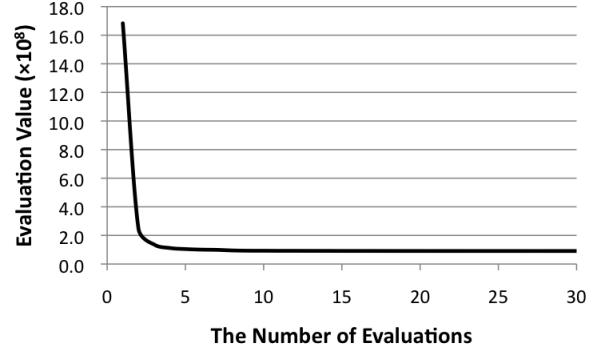


Fig. 8. Transition of the Evaluation Value by the Method of Steepest Descent

chart shown in Fig. 6. Transition of the evaluation value is shown in Fig. 8.

The horizontal and vertical axes of Fig. 8 show the number of evaluations and the evaluation values, respectively. As shown in Fig. 8, the evaluation value was converged and optimized by the steepest descent method. There are two possible reasons why the evaluation value did not reach zero. The first is that $l\theta$ and the light distribution angle is limited, while the second is that feasible illuminance distribution is limited because light spreads. The target illuminance distribution and the optimized illuminance distribution is shown in Fig. 9.

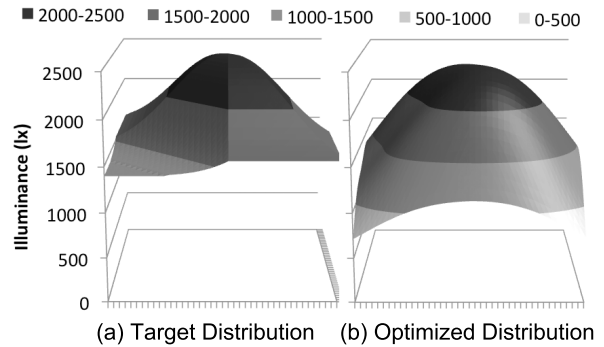


Fig. 9. Comparison of two Illuminance Distributions

In Fig. 9, the x- and y-axes of the bottom surface of the graph indicate the coordinates of the point at which measurements were taken, and the height indicates the illuminance at that point. Fig. 9 shows that a difference exists between two illuminance distribution in the same way that the evaluation value did not reach zero.

B. Numerical Experiment Results of the Learning Function

To conduct the numerical experiments regarding the learning function, an agent was created assuming this agent was a user. The agent had a two-dimensional array similar

to the system's sensory scale. The elements in this two-dimensional array were set up to have nonlinear characteristics in each dimension. The results of the system learning this agent's sensory scale (average of 30 trials) are shown in Fig. 10.

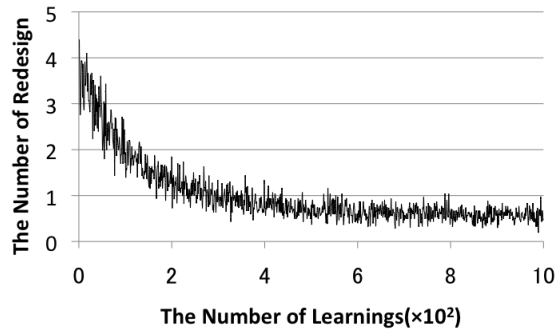


Fig. 10. Transition of the Number of Redesigns

In Fig. 10, the horizontal axis shows the number of learning steps, and the vertical axis shows the number of times which became "No" at processes (3). The learning rate and the propagation rate were set as $\alpha = 0.5$, $\beta = 0.5$, and $\gamma = 0.5$, respectively. As shown in Fig. 10, the system could learn the sensory scales of the agent because the number of redesigns (failures) decreased as the system repeated learning. Hereafter, there is a need to verify the effectiveness of the learning mechanism when the user is an actual human. Although improvement of learning speed is also an issue in this learning function, it is possible to make improvements by increasing the learning rate or the propagation rate closer to 1. Therefore, It is necessary to examine the parameter with sufficient learning efficiency.

VI. CONCLUSION

In intelligent lighting systems where lights are connected on a network and can be controlled individually, operability through existing UI is associated with a large burden on the user. In this paper, we proposed a UI to control lights by designing the illuminance distribution in such a lighting system, which learns the sensory scale of each user. In this study, it was shown that the illuminance distribution control can be optimized by the steepest descent method. In addition, we described how the feasible illuminance distribution is limited due to the physical limitations of the lighting system and the lights themselves. Therefore, we aim to improve the system such that it can provide a distribution satisfactory to the user's requirements. We also showed that the system is able to learn the sensory scales using an agent. In future studies, we will verify the effectiveness of system learning using human subjects as well as adjusting the parameters to further enhance the learning speed.

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