Proposal for an Intelligent Lighting System, and Verification of Control Method Effectiveness

Mitsunori Miki
Department of Knowledge Engineering,
Doshisha University
1-3 Tatara Miyakodani
Kyotanabe, Kyoto 610-0394
Email: mmiki@mail.doshisha.ac.jp

Tomoyuki Hiroyasu
Department of Knowledge Engineering,
Doshisha University
1-3 Tatara Miyakodani
Kyotanabe, Kyoto 610-0394
Email: tomo@is.doshisha.ac.jp

Kazuhiro Imazato
Graduate School of Engineering,
Doshisha University
1-3 Tatara Miyakodani
Kyotanabe, Kyoto 610-0394
Email: kimazato@mikilab.doshisha.ac.jp

Abstract— **In recent years, various types of equipment have become more intelligent. In this research, we propose an intelligent lighting system for providing the necessary illuminance to a desired location; actually construct a fundamental experiment system based on that concept; and verify the effectiveness of the newly developed control method. Verification tests were conducted using an optimization algorithm specialized for lighting control, and the results showed that the various illuminance sensors converged to the preset target illuminance. We also confirmed that the system can respond adaptively to the movement of illuminance sensors and contingencies like lighting malfunctions.**

I. Introduction

In recent years, electric appliances, automobiles, airplanes and a variety of other systems have become more intelligent, through autonomous control of the system's own operation to suit the user and the environment. This alleviates the load on human beings [1].

Although systems in the real world are becoming more intelligent in this way, intelligence has not been applied to lighting systems, which are a necessary and indispensable part of human life. And also, artificial lighting is one of the major electricity-consuming items in many nondomestic buildings, accounting for 20-30% of total electricity load[2]. For example, it is impossible to achieve a switching pattern other than that imposed by the electrical wiring at the time of design, and it is impossible to automatically and locally realize the appropriate illuminance. Recently, technology has been developed for individually controlling the luminance of various lights by connecting the lights to a network, and systems with a high-level human-interface have appeared [3][4][5][6]. And also, many new technologies which conserves energy using daylight and the theory of electric-lighting saving due to daylight is well understood [7]. For example, time switching and photoelectric controls have been developed to improve the efficient use of daylight and it can give excellent energy savings[8][9][10]. However, many problems still remain. For example, it is impossible to automatically provide the appropriate illuminance to an arbitrary location, or to allow other lighting to compensate illuminance in response to the failure of a lighting device. Other problems include: the inability to flexibly respond when lighting or lighting sensors are added, or when room partitions are changed.

In this research, we resolve these kinds of problems, and propose a new intelligent lighting system which conserves energy, and controls illumination to provide the appropriate illuminance at the appropriate locations. We also actually construct a fundamental experiment system based on this concept, and verify the effectiveness of the newly developed control method.

II. What is an intelligent lighting system

A. Overview of intelligent lighting system

The term "intelligent lighting system" refers to a system where multiple lighting fixtures are connected to a network, and user needs are met by cooperation of the various lighting fixtures. The following describes the features of an intelligent lighting system.

1) Autonomous distributed control: In an intelligent lighting system, there is no element with control over the entire system. Illuminance at each location is controlled by having each light perform learning operation. There is no central control unit, so the system has high robustness against malfunction, and a high reliability system can be achieved even in large-scale buildings. The system has outstanding features: It is easy to add lighting fixtures and lighting sensors, and there is no need, at installation, to set things like ID nos. and layout information for each lighting fixture or lighting sensor.

2) Achieving a switching pattern not dependent on wiring: In today's illumination systems, the only switching pattern which can be realized is that determined by the wiring pattern. However, with the intelligent lighting system proposed here, it is possible to realize an arbitrary switching pattern which is not dependent on the wiring of lights. Furthermore, it is possible to switch on lighting devices with any desired luminance. Therefore, the system conserves energy by not switching on unneeded lights.

3) Achieving autonomous lighting control: With this intelligent lighting system, the user simply sets a target illuminance, and the system can automatically determine the necessary lighting, without making the user aware of the location of lights, and thus can provide the appropriate illuminance to

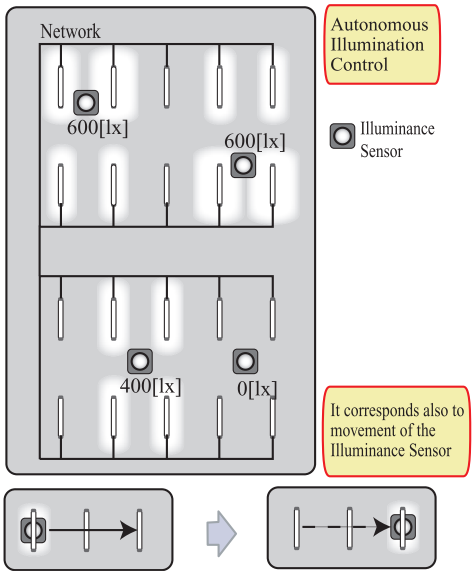

Fig. 1. Autonomous lighting control

the appropriate location. Fig.1 shows a conceptual diagram of autonomous lighting control.

B. Configuration of the intelligent lighting system

The intelligent lighting system is configured by connecting multiple intelligent lighting fixtures and multiple movable illumination sensors and power meters to a network. The term "intelligent lighting fixture" means lighting which has a controller called a learning device. This makes it possible for each individual lighting fixture to operate autonomously. Fig.2 shows the configuration of an intelligent lighting system.

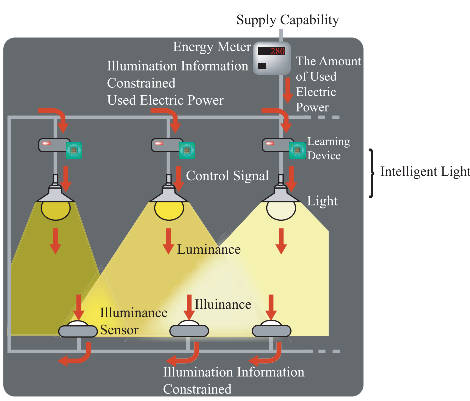

Fig. 2. Configuration of the intelligent lighting system

C. Intelligent lighting system control

The intelligent lighting system is controlled using the autonomous distributed method. Each intelligent lighting fixture controls illuminance by autonomously adjusting luminance. The control process is described below.

1) Initialize the intelligent lighting system, provide the goal of "minimizing the amount of power used" to the learning devices, and provide the constraint of "setting the illuminance of each illuminance sensor at or above a certain value" to the illuminance sensors.
2) Each illuminance sensor detects the current illuminance.
3) Each illuminance sensor sends its target illuminance and current illuminance to the network.
4) Each intelligent lighting fixture connected to the network takes in the amount of power used, and the target illumination and current illumination of each illumination sensor.
5) The learning device of each intelligent lighting fixture controls luminance based on the illumination control algorithm proposed in this research, using the amount of power, and the current and target illuminance of each sensor, which have been taken in.
6) By repeating Steps 2 to 5, the system constantly senses environmental information, and provides control so that goals and constraints are satisfied.

Using the above process, each intelligent lighting fixture learns the effectiveness of its own actions, without acquiring information from other intelligent lighting fixtures, and autonomously performs lighting control to satisfy goals and illuminance constraints. By constantly sensing environmental information, the system can respond to addition or malfunction of lights, and addition and movement of illuminance sensors.

III. Fundamental Experiment System

The fundamental experiment system is a system which was actually built based on this intelligent lighting system concept. The configuration of the fundamental experiment system is described below.

A. Hardware configuration

The hardware of the fundamental experiment system is comprised of 15 inverter controllable fluorescent lights, multiple movable illuminance sensors, and controllers for each light. Inverter control is a technology wherein luminance is adjusted by arbitrarily varying the duty ratio of a digital waveform.

B. Lighting control algorithm program

In this research, we used a newly developed autonomous distributed optimization algorithm, based on the stochastic hill climbing method, as the lighting control algorithm. The details of this algorithm are indicated below. The system uses the model in Fig.3 where each light searches using the hill climbing method, and synchronization is achieved during evaluation.

1) Perform initialization. Switch on all fluorescent lights at their initial luminance, and set target illuminance.
2) Calculate the difference between the current and target illuminance of each illuminance sensor, and calculate the objective function.
3) Calculate the amount of luminance variation, and switch on each lighting fixture at the new luminance.

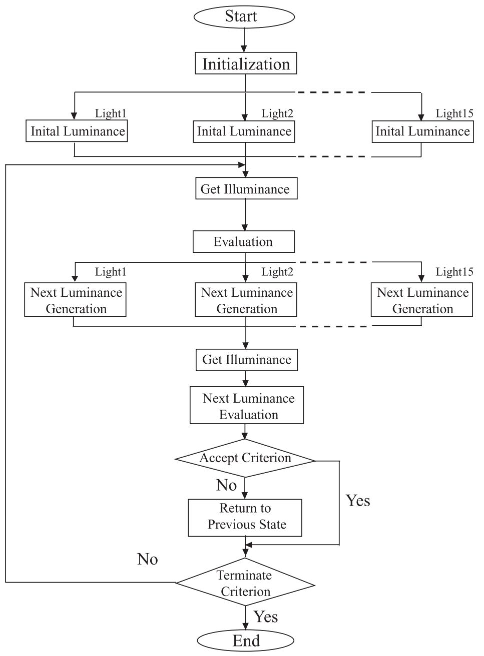

Fig. 3. Application to the intelligent lighting system

4) Calculate the objective function value from the difference between the varied illuminance and the target illuminance. If the objective function value is satisfactory, set that luminance and return to Step 2.
5) . If the objective function value worsened in Step 4, cancel the provided amount of luminance variation, and return to Step 2.

The above operation should lead to convergence to the target illuminance. The reason why the procedure does not return to Step 3 if the luminance variation is set in Step 4 is to make the system respond to environmental changes like external light shining in within the operation time in Step 4.

The goals of the intelligent lighting system are to bring the illuminance close to the target illuminance for each sensor, and to minimize electric power. In other words, these goals must be properly formulated in the objective function. The objective function used in this algorithm is indicated in Equation1.

$$f = \sum_{i=1}^{n} g(i) + w \sum_{j=1}^{m} Br(j) \quad (1)$$

$$g(i) = \begin{cases} 0 & (Lc_i - Lt_i) \geq 0 \\ (Lc_i - Lt_i)^2 & 0 > (Lc_i - Lt_i) \end{cases}$$

In this algorithm, the goal is to minimize f in Equation1. f is the sum of $g(i)$, which indicates the illuminance difference between the current and target illuminance, and $Br(j)$ which is the light luminance. $g(i)$ is added only if the illuminance difference is negative. In other words, light is increased rapidly if the current illuminance is less than the target illuminance. The luminance $Br(j)$ has a linear relationship with the energy consumed, and here it is taken to be the power used by each light. This Br(j) is multiplied by a weight w. The value of this weight determines whether priority will be placed on optimizing target illuminance, or on optimizing electric power.

IV. Validation experiment setting

Fig.4 shows the experiment environment. Experiments were conducted using the 3 patterns indicated below, and we verified that the fundamental experiment system can achieve autonomous illuminance control.

1) Experiment 1: When the environment is fixed
   The target illuminance of the illuminance sensors in the set up was set to: 400[lx] for sensor A, 500[lx] for sensor B and 550[lx] for sensor C. The arrangement of illuminance sensors is shown in Fig.4.
2) Experiment 2: When an illuminance sensor is moved
   The illuminance sensor C was moved from its state in Experiment 1 to the center position between Lights 4, 5, 9 and 10.
3) Experiment 3: When an intelligent light fixture malfunctions
   Light 7 is made to fail in the state in Experiment 2.

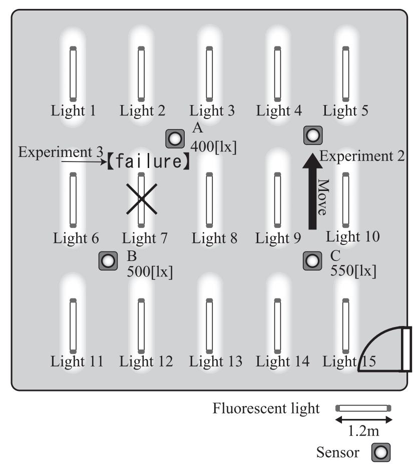

Fig. 4. Experiment environment

The parameters used in the experiment are shown in Table I. In these experiments, the luminance was varied in increments of 2% of the maximum luminance.

TABLE I
EXPERIMENT PARAMETERS

Number of fluorescent lights	15
Number of illuminance sensors	3
Target illuminance [lx]	400,500,550
Distribution of light increase/decrease [%]	+8,-8,+6,-6,+4,-4,+2,-2,0
Initial luminance [cd]	All 1050
Weight (w)	1.7

V. Experiment results

A. When the environment is fixed

This section describes the experiment results when the environment was fixed. Fig.5,6, and 7 show the history of illuminance at each illuminance sensor, luminance of each light, and the objective function value

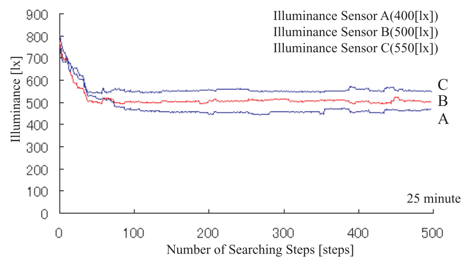

Fig. 5. Illuminance history

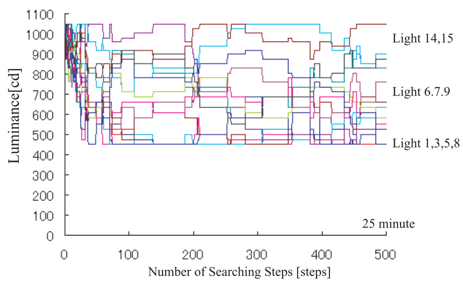

Fig. 6. Luminance history

Fig. 7. Objective function value history

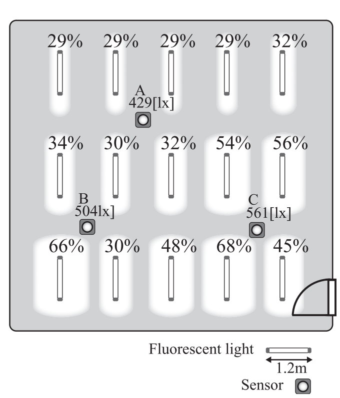

Fig. 8. Luminance of each light in the steady state

As you can see in Fig.5, after the start of the experiment, the initial illuminance decreases, and when the number of searching steps is 100 (300 seconds), the illuminance at illuminance sensors A, B and C becomes, respectively, 460, 500 and 555[lx], so the luminance converges to a value close to the target illuminance. As you can see in Fig.7, as search proceeds, the objective function value decreases, so electric power is minimized. Electric power in the steady state is reduced by about 47% compared to the initial state.

Fig.8 shows the luminance of each light [in %, i.e. the ratio against the luminance when the maximum switched on luminance is taken to be 100%].

B. When an illuminance sensor is moved

This section describes the experimental results when the illuminance sensor was moved. Fig.9, and 10 show the history of illuminance at each illuminance sensor, and of the objective function value. The horizontal axis of each graph is the number of searching steps.

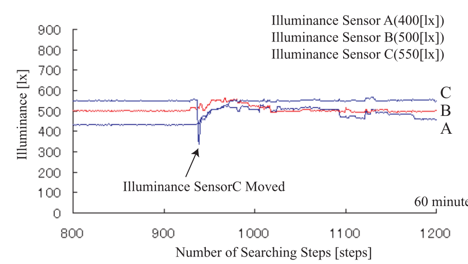

Fig. 9. Illuminance history

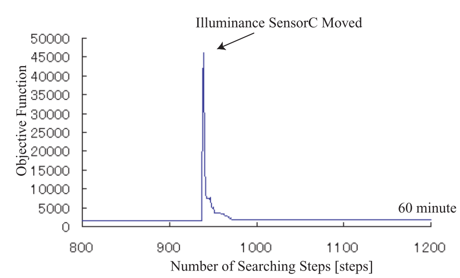

Fig. 10. Objective function value history

In Fig.9, the value of illuminance sensor C when it is moved (i.e. when the number of searching steps is approx. 950) is much less than the target illuminance. From Fig.10, you can confirm that the environment changed because the objective function value at that time changed to a high value. The illuminance of the illuminance sensors was, respectively, 438, 500 and 557[lx] before moving illuminance sensor C. Fig. 11 shows the luminance [%] of each light before movement. In Fig. 9, you can see that after illuminance sensor C is moved, it takes about 50 searching steps (i.e. 150 seconds) for the illuminance of illuminance sensor C (which was below the target illuminance) to reach the target illuminance.

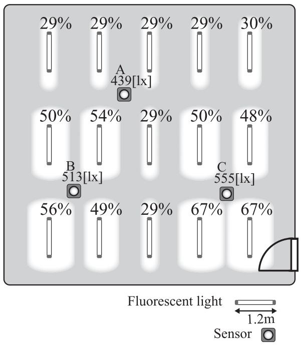

Fig. 11. Before moving

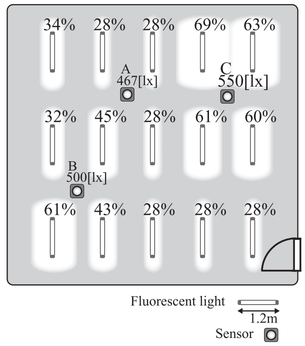

Fig. 12. Steady state

In the steady state, the illuminance of the illuminance sensors becomes 467, 500 and 550 [lx] so the algorithm has almost converged on the target illuminance. The reason why the illuminance of illuminance sensor A is higher than the target illuminance is that movement of illuminance sensor C caused an increase in the luminance of lights 4 and 9, which have an effect on illuminance sensor A.

Fig.12 shows the luminance [%] of each light in the steady state. Comparing Fig.11, and 12, we see that luminance was increased at lights 4, 5, 9 and 10 (at the location where sensor C was moved to), and that the luminance of lights 14 and 15 dropped because they no longer affect any illuminance sensor. Therefore, we see that this system can respond to movement of illuminance sensors.

C. *When an intelligent light fixture malfunctions*

This section describes the experimental results when an intelligent light fixture malfunctions. Fig. 13, 14, and 15 show the history of illuminance at each illuminance sensor, luminance of each light, and the objective function value. The horizontal axis of each graph is the number of searching steps.

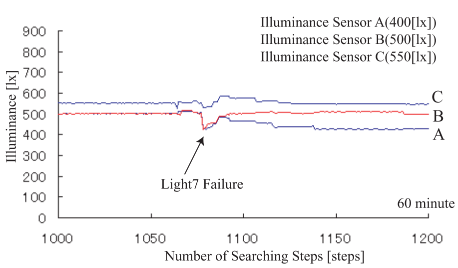

Fig. 13. Illuminance history

As you can see in Fig.14, the luminance dropped to 0 [cd] at the time light 7 malfunctioned (i.e. when the number of searching steps was approx. 1080). Therefore, the illuminance of illuminance sensor B dropped below the target illuminance, as you can see in Fig.13. From Fig.15, you can also confirm that the environment has changed because the object function value changed to a high value when the malfunction occurred. The illuminance of each illuminance sensor before light 7 malfunctioned was, respectively 507, 501 and 552 [lx]. Fig.16

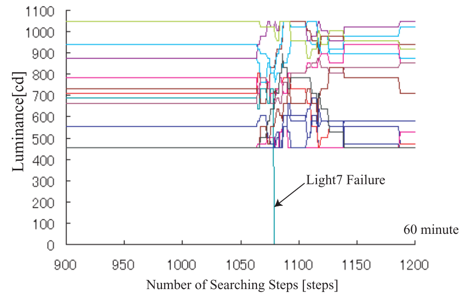

Fig. 14. Luminance history

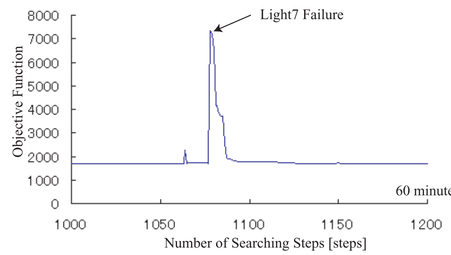

Fig. 15. Objective function value history

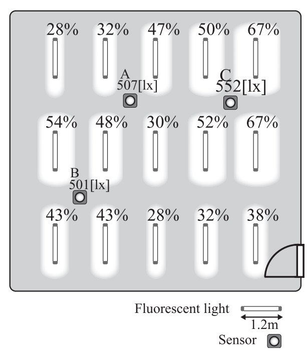

Fig. 16. Before light malfunction

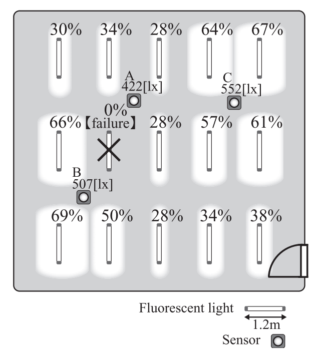

Fig. 17. Steady state

shows the luminance [%] of each light before the malfunction. In Fig.14, you can see that after light 7 malfunctions, it takes 30 searching steps (i.e. about 90 seconds) for the illuminance of illuminance sensor B to reach the target illuminance.

In the steady state, the illuminance of the illuminance sensors becomes 422, 507 and 552 [lx] so the algorithm has almost converged on the target illuminance. The luminance [%] of each light in the steady state is shown in Fig.17. Comparing Fig.16, and 17, we see that the luminance of lights 6, 11 and 12 increased to compensate for the brightness of light 7, which malfunctioned. So we see that this system can handle light malfunctions.

VI. Conclusion

In this research, we proposed an intelligent lighting system which can contribute to energy saving, and which can provide the desired illuminance at a desired location based on information from movable illuminance sensors. A fundamental experiment system using fluorescent lights was built, and tests were conducted using the proposed autonomous distributed control algorithm. We confirmed that the system operates appropriately. For these reasons, we believe that the intelligent lighting system proposed in this research is an effective, reliable lighting system which greatly surpasses previously developed high-level lighting systems.

REFERENCES

[1] MIKI M, KAWAOKA T Design of Intelligent Arti-facts:A Fundamental Aspects *Proc.JSME Inter-national Symposium on Optimization and Innova-tive Design*(OPID97), 1997-9.

[2] LAM JC, CHAN ALS Energy audits and surveys of air-conditioned buildings. *Proceeding of Australian and New Zealand Architectural Science Association Conference*, Univercity of Canberra, Australia 1995, Page49-54.

[3] Lighting controls *Int Light Rev*, Vol.49, No.981, Page48-49(1998)

[4] PETERSON D, RUBINSTEIN F Effective lighting control. *LD+A*, Vol.13, No.2, Page18-23, (1983.02)

[5] RUBINSTEIN F 50 Percent Energy Savings with Automatic Lighting Controls. *Strateg Plann Energy Environ*, Vol.11, No.2, Page17-31, (1991)

[6] ALONSO J M, RIBAS J, DEL COZ J J, CALLEJA A J, LOPEZ E, RICO-SECADES M Intellignt Control System for Fluorescent Lighting Based on LonWorks Technology. *Proc IEEE IECON*, Vol.1998, No.Vol.1, Page92-97, (1998)

[7] WILKINSON MA The effect of glazing upon energy consumption within buildings. *Lighting Research and Technology*, Vol.24, No.2, Page99-101, 1992

[8] LITTLEFAIR PJ Predicting lighting energy use under daylight linked lighting controls. *Building Research and Information*, Vol.26, No.4, Page208-220, 1999.

[9] SLATER AI, BORDASS WT, HEASMAN TA, People and lighting controls. *BRE information paper IP 6/96*,Garston: CRC,1996.

[10] LI DHW, Lam JC An inverstigation of daylighting performance and energy saving in a daylit corridor. *Energy and Buildings.*