Preliminary Evaluation of
the Intelligent Lighting System with Distributed Control Modules

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Abstract—In our laboratory, Intelligent Lighting System is proposed as lighting control system targeting office environment. Currently, a verification experiments of Intelligent Lighting System is conducted in an actual office. In the verification experiments conducted in large scale offices, an issue of complex wiring was clarified. Intelligent Lighting System uses analog communication for the information acquisition from the illuminance sensors. Therefore, the wiring becomes complex when the system becomes large. On the other hand, Intelligent Lighting System has been studied as a distributed control system equipped with an individual lighting control device, but the systems that used in the verification experiments are centralized control systems that controls all lighting fixtures with one centralized control device. Because of the high development cost of the control device which can be equipped in a lighting fixture. However, these system configurations have the different features, respectively. Therefore, appropriate system configuration is different by the office which introduces Intelligent Lighting System. In this study, we develop illuminance sensors with digital communication technology in order to solve the complexity of wiring. Additionally, distributed control Intelligent Lighting System is constructed by using the proposed control devices which can be equipped in a lighting fixture, and its illuminance convergence is verified.

Keywords-Optimization, Lighting Control, Distributed Control, Office Environment

I. 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. 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].

On the other hand, improvement of office workers' intelligent productivity, creativity and comfortableness in offices has been focused on in recent years[2]. And 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, our laboratory has been conducting research on Intelligent Lighting System which provides illuminance appropriate for office workers' needs. Intelligent Lighting System allows each worker to set the ideal illuminance on his/her own illuminance sensor. The system can achieve a lighting pattern with the smallest electric power and at the same time satisfy the set illuminance value by using optimization method. Verification experiments have been conducted for actual use in offices[4]. In the verification experiments conducted in large scale offices, an issue of complex wiring was clarified. Intelligent Lighting System uses analog communication for the information acquisition from the illuminance sensors. Therefore, the wiring becomes complex when the system becomes large. On the other hand, Intelligent Lighting System has been studied as a distributed control system equipped with an individual lighting control device, but the systems that used in the verification experiments are centralized control systems that controls all lighting fixtures with one centralized control device. Because of the high development cost of the control device which can be equipped in a lighting fixture. However, these system configurations have the different features, respectively. Therefore, appropriate system configuration is different by the office which introduces Intelligent Lighting System.

In this study, we develop illuminance sensors with digital communication technology in order to solve the complexity of wiring. Additionally, distributed control Intelligent Lighting System is constructed by using the proposed control devices which can be equipped in a lighting fixture, and its illuminance convergence is verified.

Illuminance means physical quantity that indicates incoming luminous flux into unit area, and described with lx (lux). The later described luminance is physical quantity that indicates luminous flux per unit solid angle radiated from light source to certain direction, and described with cd (candela).

II. INTELLIGENT LIGHTING SYSTEM

A. Onerview of the Intelligent Lighting System

Intelligent Lighting System consists of control devices, lighting fixtures, illuminance sensors and an energy meter connected to the intelligent lighting system network. Control device controls luminance of lighting fixture in accordance with autonomous distributed algorithm above described based on illuminance information from illuminance sensors and power information from an energy meter. The concept of Intelligent Lighting System is indicated in Fig.1.
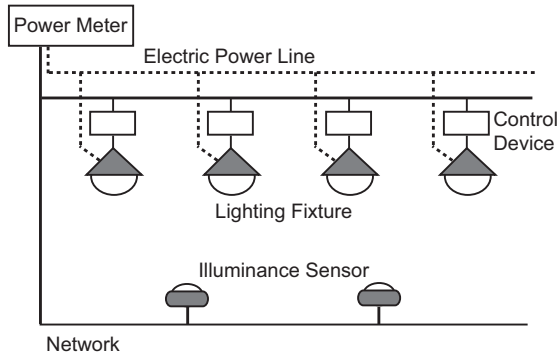

Fig. 1. The concept of Intelligent Lighting System

Individual users set the illuminance constraint on the illuminance sensors. At this time, each light repeats autonomous changes in luminance to converge to an optimum ligthing pattern.

B. Control of Intelligent Lighting System

In Intelligent Lighting 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].

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 objective function is indicated in the Equation 1.

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

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

$$g_j = \begin{cases} 0 & (Ic_j - It_j) \geq 0 \\ R_j \times (Ic_j - It_j)^2 & (Ic_j - It_j) < 0 \end{cases}$$

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

n:Number of illuminance sensors, m:Number of lighting fixtures, w:Weight, P:Electric energy, Ic:Current illminance, It:Target illuminance, L: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.

C. Introduction Example

Presently, Intelligent Lighting System is under a verification experiment in some offices in the aim of commercial use[4]. Introduction offices are shown below.

- Kokuyo Co., Ltd. Eco Liveoffice Shinagawa
- Mitsubishi Estate Co., Ltd. Area Planning Office
- Mitsubishi Estate Co., Ltd. Management Building Office
- Mitsubishi Estate Co., Ltd. Ecozzeria
- Mori Building Co., Ltd. headquarters
- Mitsubishi Electric Co. headquarters

There are 22 office workers working on a floor of 16m x 15m in Urban Design Office in Otemachi Building (Otemachi, Chiyoda-ku, Tokyo) owned by Mitsubishi Real Estate Services. Fig.2 shows system configuration of the introduced system in Urban Design Office. As shown in Fig.2, Urban Design Office is equipped with one system control computer, twenty-six lighting fixtures (two daylight fluorescent light tubes and one light bulb color fluorescent tube), six light control interfaces (ten channels for each device), twenty-two illuminance sensors and two A/D converters (sixteen channels for each device). Light control interface

is a device that can control luminance of lighting fixture by changing duty ratio of wave pulse based on Pulse Width Modulation (PWM) Method. As described above, Intelligent Lighting System control requires illuminance information from illuminance sensor and power information from power sensor. Illuminance information from illuminance sensor is outputted in analog signal. Therefore, system control PC acquires illuminance information after converting it to digital signal through A/D converter. Power information is estimated based on luminance information of each lighting fixture controlled by system control PC because power volume and a sum of illuminance of each lighting fixture are in proportional relation.
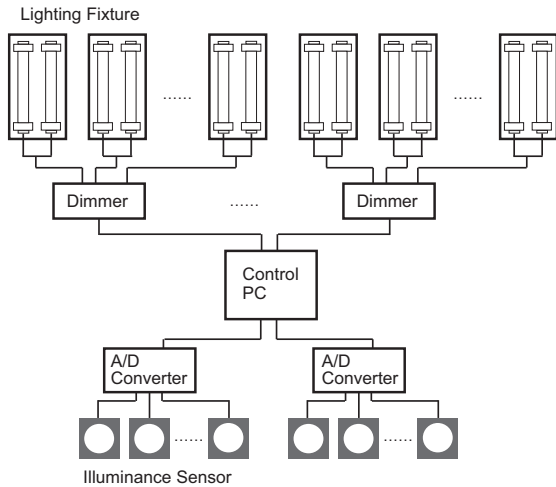

Fig. 2.   System configuration of the introduced system

Fig.3 shows history of illuminance of a typical illuminance sensor. Actual illuminance can be confirmed to match target illuminance set by a user in Fig.3. Illuminance value from noon to 13:00 is low because this time slot is lunch break and lightings of the entire building are turned off. Actual illuminance increases a little before the time when target illuminance is set because it is influenced by outer light from the window and lighting fixture near an office worker who arrives at work earlier.
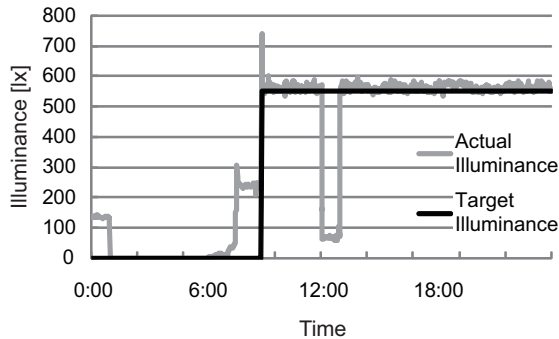

Fig. 3.   History of illuminance of a typical illuminance sensor

D. Issues of System Configuration in the Actual Environment

The office for introduction referred in Paragraph II-C has at maximum thirty lighting fixtures and forty-two illuminance sensors and is larger compared to the laboratory. Therefore, an issue of introduction such that wiring of Intelligent Lighting System is complex was clarified.

The reasons of complexity of Intelligent Lighting System wiring is that communication between illuminance sensor and A/D converter is analog signal, and also that wiring must be done in accordance with unique ID allocated to each device. Fig.4 shows wiring status of illuminance sensor and A/D converter.

Fig. 4.   Wiring status (Placed under the floor)

On the other hand, Intelligent Lighting System has been studied as a distributed control system equipped with an individual lighting control device, but the systems that used in the verification experiments are centralized control systems that controls all lighting fixtures with one centralized control device. Because of the high development cost of the control device which can be equipped in a lighting fixture. However, these system configurations have the different features, respectively. Therefore, appropriate system configuration is different by the office which introduces an intelligent lighting system.

Therefore, in this study, we develop illuminance sensors with digital communication technology in order to solve the complexity of wiring. Additionally, distributed control Intelligent Lighting System is constructed by using the proposed control devices which can be equipped in a lighting fixture, and its illuminance convergence is verified.

III. PROPOSED SYSTEM

A. System Configuration

System configuration in Intelligent Lighting System is divided into connection system and control system. Intelligent Lighting System configuration currently under verification experiments is as described in Paragraph II-C. Illuminance sensor and A/D converter is communicated through analog communication. All lighting fixtures are controlled by one

control PC. Therefore, this system configuration is called analog centralized control system.

In order to resolve wiring complexity, analog connection system is changed to digital system. On the other hand, control system is changed to distributed control system to resolve reliability problem. Intelligent Lighting System uses autonomous distributed algorithm for control, which allows it to be reliable distributed control system. In distributed control system of Intelligent Lighting System, each control device determines luminance of each lighting system by mounting control device on each lighting fixture. This system configuration proposed in this study is called digital distributed control system. Fig.5 shows digital distributed control system configuration.
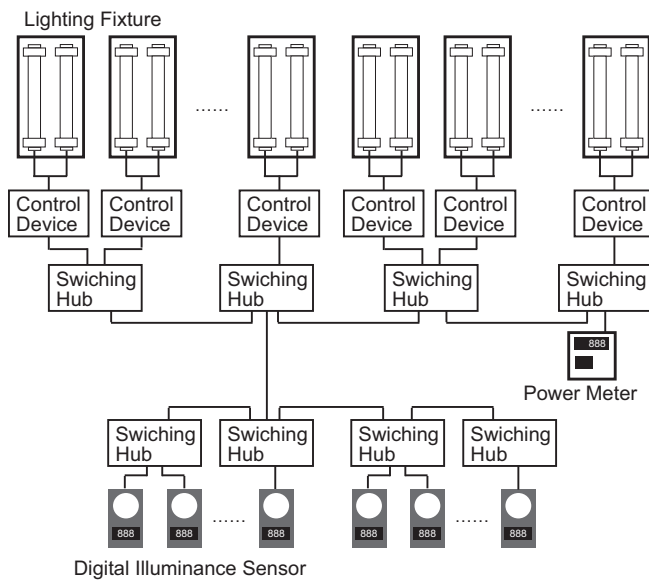

Fig. 5. Configuration of the digital distributed control system

As shown in Fig.5, digital distributed control system consists of lighting fixture with control device, power sensor, illuminance sensor and switching hub. It does not thus require wiring in accordance with unique ID of each device. Furthermore, it is possible to give redundancy to communication path. Additionally, in distributed control system, control device mounted on each lighting fixture determines luminance of each lighting fixture based on illuminance information from illuminance sensor and power consumption information from power sensor. Although one control device breaks down, other control devices can continue operating in this way.

B. Comparison of System Configurations

Analog centralized control system and digital distributed control system have respectively different features. Next, important items are compared for commercialization of Intelligent Lighting System.

- Cost

  Connection System

  Analog system does not require lighting fixtures and illuminance sensors dedicated for Intelligent Lighting System. This means that any existing controllable lighting fixtures installed in an office may be used. On the other hand, in digital system, there is no lighting fixture and illuminance sensor that can be connected to network. Therefore, devices dedicated for Intelligent Lighting System need to be developed.

  Control System

  PC can be used as control device in centralized control system while distributed control system needs development of control device that can be mounted on lighting fixture.

- Serviceability

  Connection System

  In analog system, wiring becomes more complex as the system becomes larger. On the other hand, digital system can transmit data to a designated receiver. Therefore, hardware can be changed without consideration of complex wiring.

  Control System

  Centralized control system has 1 control device and software can be easily changed. On the other hand, in distributed control system, it is not easy to change software of all control devices since it has multiple control devices and control devices are mounted on lighting fixtures.

- Reliability

  Connection System

  Analog system is not good at breakdown resistance since there is no redundancy in wiring. On the other hand, digital system is better at breakdown resistance because it can give redundancy to wiring.

  Control System

  Centralized control system is not good at breakdown resistance since there is only 1 control system. On the other hand, distributed control system is better at breakdown resistance since control devices are distributed in multiple ways and each control device operates with autonomous distributed control algorithm.

- Illuminance Convergence

  Connection System

  No difference between connection systems for illuminance convergence.

  Control System

  The present centralized control system controls lighting fixture in synchronization. On the other hand, the control of lighting fixtures becomes asynchronous in the distributed control system. However, The illuminance convergence of distributed control systems has not been investigate so far.

Considering the above matters, in regard to commercialization, there is a great advantage for a small office to introduce analog centralized control system which is better in cost and serviceability. However, it is necessary to introduce digital distributed control system in a large office from the viewpoint of reliability. We construct the digital distributed control Intelligent Lighting System and verify the convergence of illuminance.

IV. VERIFICATION OF EFFECTIVENESS OF THE PROPOSED SYSTEM

A. System Construction

Fig.6 shows hardware configuration of digital distributed control Intelligent Lighting System constructed in this study.
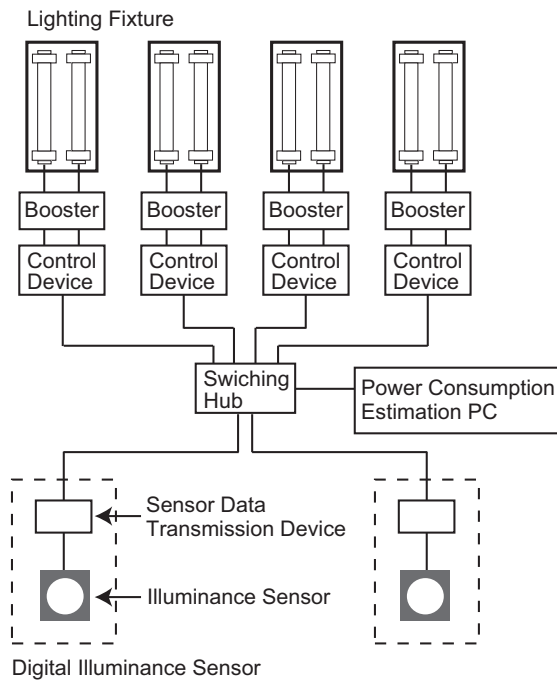

Fig. 6. Hardware configuration of the system constructed in this study

As indicated in Fig.6, hardware configuration of the constructed system consists of four Panasonic fluorescent lighting fixtures (two daylight fluorescent light tubes), two Digital illuminance sensors, four control devices and one power consumption estimation PC. These digital illuminance sensors are composed of an DeltaOHM illuminance sensor and an sensor data transmission device.

Control device controls luminance of lighting fixture in accordance with autonomous distributed algorithm above described based on illuminance information from sensor data transmission device and power information from power consumption estimation PC. In addition, current luminance information is transmitted to power consumption estimation PC to estimate power consumption. Sensor data transmission device estimates power consumption based on a sum of luminance of lightings received from control device and

transmits to all control devices. This is because it was difficult to obtain device that measures and transmits power consumption in real time. It was confirmed in the preliminary experiment that relation of a sum of lighting luminance and power consumption can be approximated in the primary expression.

In this system, Renesas Electronics 16 bit microprocessor (H8/3069F) is used as control device and sensor data transmission device. For use of H8/3069F, Nissho Technology's Kane BeBe H8/3069F board (hereinafter, H8/3069F board) was used. H8/3069F board is equipped with Ethernet controller (RTL8019AS) which is compliant with IEEE-compliant 10BASE-T, and is communicable with TCP/IP. Lighting luminance is controlled based on PWM Method, but lighting is controlled through booster circuit because lighting input voltage was 10 V while H8/3069F board output voltage was 5 V.

B. Verification Experiment

In order to verify illuminance convergence of the proposed system, a verification experiment was conducted in the experiment environment shown in Fig.7. Four lighting fixtures and two illuminance sensors were used for the test. The lighting fixtures were placed in one line, and illuminance sensor A was placed in a position equally distanced from lighting fixture 1 and 2. illuminance sensor B was placed right under lighting fixture 3. Positioning interval 1.8 m for lighting fixtures is used in general Japanese offices.
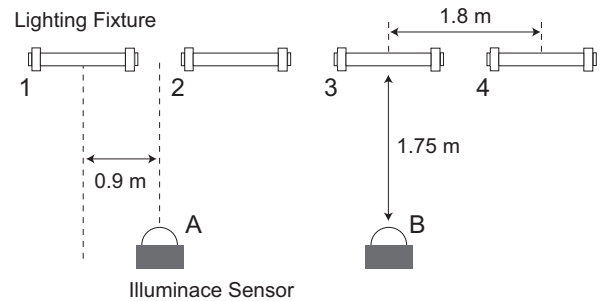

Fig. 7. Experimental environment

In this experiment, target illuminance of illuminance sensor A and B was respectively set as 450 and 550 lx. Target illuminance of illuminance sensor A of approximately 360 seconds later was changed to 700 lx. These target illuminances were highly selected by office workers in the verification experiments in an office building. History of illuminance acquired from the experiment is shown in Fig.8, history of luminance in Fig.9, and history of power consumption in Fig.10 respectively. Power consumption shown in Fig.10 is ratio with assumption that power consumption was 100 when general lighting fixtures without light control were lightened up.
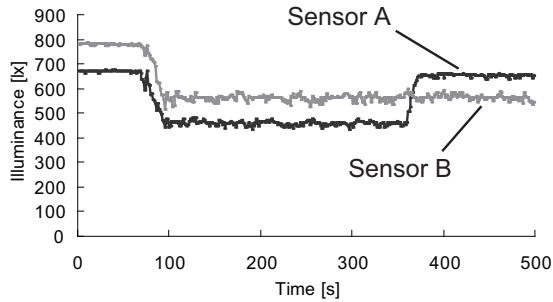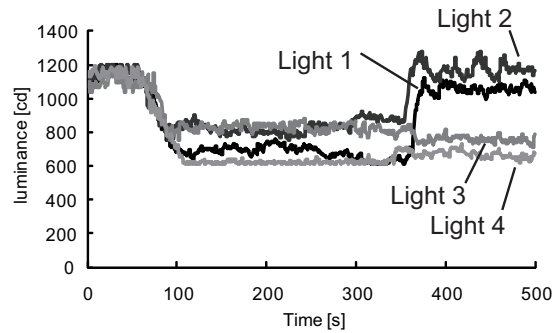
Fig. 8.   History of illuminance
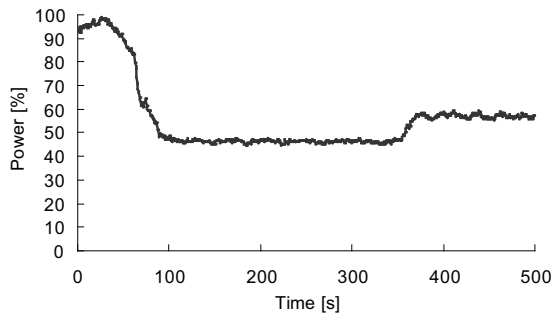

Fig. 9.   History of luminance

Fig. 10.   History of power consumption

Fig.8 shows that achieved illuminance of each illuminance sensor converged to target illuminance in approximately 100 seconds. Difference between target illuminance and achieved illuminance of each illuminance sensor was within 50 lx. Illuminance difference which can be recognized by human in office environment is about 50 lx [6], so each illuminance sensor is considered to achieve target illuminance. Also when target illuminance of illuminance sensor A is changed, achieved illuminance converged to target illuminance in approximately 20 seconds.

Fig.9 also shows that luminance of each lighting fixture is stabilized in approximately 100 seconds. Luminance rapidly converges after approximately 50 seconds because regres-

sion analysis described in II-B was properly done. In the period from 100 seconds when illuminance converged and to 360 seconds when target illuminance of illuminance sensor A was changed, luminance of lighting fixture 2 and 3 placed inside is higher compared with that of lighting fixture 1 and 4. This is because energy saving is improved when lighting fixture 2 and 3 placed inside achieve illuminance of illuminance sensor A and B. In the period from 360 to 500 seconds when target illuminance of illuminance sensor A was changed, the changed illuminance of illuminance sensor A is achieved by higher luminance of lighting fixture 1 and 2, among which lighting fixture 2 has higher luminance because it can achieve illuminance sensor B at the same time.

Fig.10 shows that power consumption is restrained around 40 % to 50 %, which confirms that it is lighting pattern with consideration of energy saving.

From the above matters, digital distributed control Intelligent Lighting System proposed in this study can achieve target illuminance set by illuminance sensor and achieve lighting pattern with consideration of energy saving.

V. CONCLUSION

In this study, we proposed a digital distributed control Intelligent Lighting System and conducted the verification experiment. As a result of the verification experiment, it was confirmed that the proposed system can achieve target illuminance and achieve lighting patter with consideration of energy saving. In the future, a verification experiment in larger system and long-term verification experiments are considered to be necessary.

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