Intelligent Lighting System using Visible-Light Communication Technology

Mitsunori Miki
Department of Knowledge Engineering
Doshisha University
Kyoto, Japan
Email:mmiki@mail.doshisha.ac.jp

Emi Asayama
Graduate School of Engineering
Doshisha University
Kyoto, Japan
Email:asayama@mikilab.doshisha.ac.jp

Tomoyuki Hiroyasu
Department of Knowledge Engineering
Doshisha University
Kyoto, Japan
Email:tomo@is.doshisha.ac.jp

***Abstract*— In recent years, various types of equipment have become more intelligent. In this research, we propose an intelligent lighting system using visible-light communication technology for direct communication between lighting fixtures and illuminance sensors in order to provide the necessary illuminance to a desired location. We actually constructed an experiment simulator based on this concept and verified 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 in a very short time. We also confirmed that the system can respond adaptively to the movement of illuminance sensors.**

***Keywords*—intelligent, lighting systems, autonomous distributed control, energy saving, intelligent system, visible-light communication, fluorescent lamps, cofficient correlation**

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. 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 lighting 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]. And also, there are many new technologies which conserve energy using daylight and the theory of electric-lighting saving due to daylight is well understood [6]. For example, time switching and photoelectric controls have been developed to improve the efficient use of daylight and this can give excellent energy savings [7] [8] [9]. 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 illuminance sensors are added, or when room partitions are changed.

On the other hand, we have resolved these kinds of problems, and proposed a new intelligent lighting system [10] which conserves energy, and controls illumination to provide the appropriate illuminance at the appropriate locations. As an intelligent lighting system control algorithm, the "Adaptive Neighborhood Algorithm using Correlation Coefficient" (ANA/CC) [11] was proposed. By comprehending the location information of lighting fixtures and illuminance sensors through a correlation, this control algorithm facilitates the convergence within a short period of the two factors of target illuminance and an energy conservation condition. We also have actually constructed a fundamental experiment system based on this concept, and verify the effectiveness of this control algorithm.

However, there are two problems within ANA/CC. One problem is that the correlation might not be taken correctly due to illuminance sensor distribution location. This problem becomes an unavoidable truth in large-scale environments. The second problem is that when illuminance sensors are moved, instantaneous response is impossible to pertain to the calculation of correlation coefficient.

In this research, we resolve these problems, and propose a new intelligent lighting system, which visible-light communication (VLC) [12] is introduced into. Direct communication between lighting fixtures and illuminance sensors should allow the location information to be instantly comprehended. We will examine the effectiveness in the case of introducing visible-light communication into an intelligent lighting system. Also, we will develop algorithms to control the system.

II. What is an intelligent lighting system

A. Overview of intelligent lighting system

The term "intelligent lighting system" [10] 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.

- 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 illuminance sensors, and there is no need, at installation, to set things like ID nos. and layout information for each lighting fixture or illuminance sensor.
- Achieving autonomous lighting Control
  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 lighting fixtures. Furthermore, it is possible to switch on lighting devices with any desired luminance. Therefore, the system conserves energy by not switching on unneeded lighting fixtures.

B. *Configuration of intelligent lighting system*

The intelligent lighting system is configured by connecting multiple intelligent lighting fixtures and multiple movable illuminance 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. Based on the illuminance information that flows through the network, individual control devices apply the optimal algorithm and exert control autonomously, facilitating the optimum lighting pattern.

The lighting control algorithm being used presently is called "Adaptive Neighborhood Algorithm using Correlation Coefficient" (ANA/CC) [11]. It incorporates a mechanism based on a correlation coefficient for lighting control with the general purpose optimizing method called "Stochastic Hill Climbing" (SHC) as a base. The fact that a correlation coefficient exists indicates that two or more phenomena become a set and change together. The algorithm calculates the correlation from "the amount of luminous intensity changed" and "the amount of illuminance intensity changed". In the algorithm, comprehension of the location information of lighting fixtures and illuminance sensors is effective in quickly converging the good conditions of fulfilling the target illuminance and conserving energy.

Fig.1 shows the example of the distance of lighting fixtures and illuminance sensors and the correlation coefficient history. The horizontal axis is the number of steps. The correlation between Light 1 and the Sensor is high, and low for Light 2 and 3. This information is used in the next luminance generation. And lighting fixtures which have illuminance sensors in near distance should change the luminance to appropriate luminance intensity to satisfy the target illuminance.

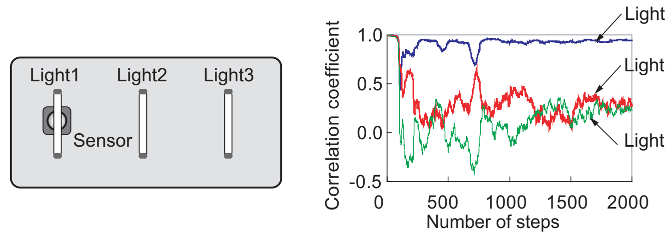


Fig. 1. Correlation of luminance and illuminance

III. Examination of Intelligent Lighting System using Visible-Light Communication Technology

A. *Visible-light communication technology*

Recently, as new communication technology, visible-light communication (VLC) technology [12] which uses visible-light to conduct communication has been receiving attention. As compared with the technology of infrared communication which already exists, the feature of visible-light communication technology is described below.

- Because electricity used in lighting can be applied directly to communication, it is possible to construct wireless communication environments with simple equipment.
- Because light is not regulated by any radio law, it can be used even in areas where electric waves are restricted.
- Because communication is conducted via visible-light, transmission and reception can be confirmed by visual inspection, making it superb for security issues, etc.

Elements that emit visible-light are visible-light LED, visible-light laser, organic EL, fluorescent lamps, etc. For the proposed intelligent lighting system, fluorescent lamps with visible-light communication technology installed [13] will be examined.

B. *Outline of proposed system*

We propose an intelligent lighting system using visible-light communication technology in order to accelerate the convergence to the preset target illuminance. A device that transforms electrical signals into light in the lighting fixtures and a receiver terminal in the illuminance sensors are added to the conventional system. Fig. 2 displays the configuration of this system.

In this system, the ID is given to each lighting fixture, and the ID is carried on the light by the modulation of the visible-light. The illuminance sensors can obtaine the IDs of the lighting fixtures directly. Therefore, the location information of each lighting fixtures and illuminance sensors can be grasped by whether the lighting ID was acquired. Compared with the conventional system, since grasp of location information does not take time, the convergence to target illuminance becomes early.

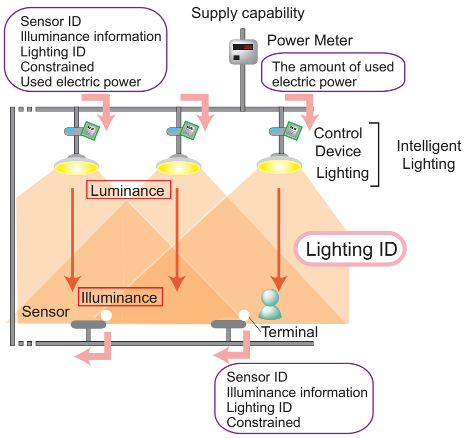


Fig. 2. Configuration of the intelligent lighting system using VLC

C. Introduction of visible-light communication technology

Three types of methods for comprehension the location information of the lighting fixtures and illuminance sensors can be considered in introducing visible-light communication technology into the intelligent lighting system. The 1st type is the method where only visible-light communications are used, and the 2nd is the method where visible-light communications and ANA/CC are used exclusively depending on the different situation. And the 3rd is the method that combines visible-light communications and ANA/CC. In this research, we use the 3rd type method, because the rough location information on lighting fixtures and illuminance sensors can be grasped by using visible-light communications and the detailed location information on them can be grasped by using ANA/CC.

D. Control algorithm

The control algorithm for this system is ANA/CC as a base incorporated with visible-light communication. This will be referred to herein as ANA/CC with Visible-Light Communication (ANA/CC+VLC). Visible-light communication is used to comprehend the location information of the lighting fixtures and illuminance sensors. The flow of this algorithm is displayed in Fig. 3, and explained below.

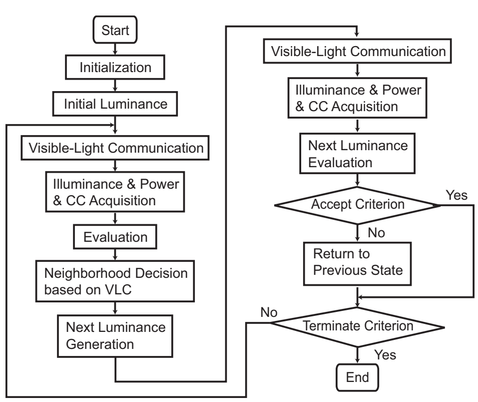


Fig. 3. Adaptive Neighborhood Algorithm using Correlation Coefficient with Visible-Light Communication (ANA/CC+VLC)

1) The initial parameters such as initial luminance and target illuminance are set, and individual lighting fixtures illuminate at the initial luminance.
2) The lighting ID is transmitted using visible-light communication.
3) Individual lighting fixtures acquire individual illuminance sensor information (illuminance sensor ID, current illuminance, target illuminance, and transmitted lighting ID) and electricity usage amount from power meters, and calculate the correlation from the illuminance and luminance.
4) Calculate an objective function value.
5) The appropriate neighborhood is determined based on the sensor information.
6) The next luminance is generated randomly within the determined neighborhood, and lighting fixture is applied at that luminance.
7) Individual lighting fixtures acquire the sensor information and electricity usage amount and calculate the correlation from the new illuminance and new luminance.
8) Calculate the objective function from new illuminance and electricity usage amount.
9) If the objective function value is improved, that luminance is set. Return to step 2.
10) If the objective function value from step 6 degenerates, the luminance change is canceled. Return to step 2.

By performing the above operation, it can converge to the target illuminance and to a power saving state. The reason for returning to step 2 from steps 7 and 8 is to respond to alterations in the environment such as outside light, etc.

E. Objective function used in this algorithm

The objectives of autonomous lighting control for the intelligent lighting system are to bring the illuminance close to the target illuminance of each illuminance sensor and to minimize electricity usage amount. The objective function used in the proposed algorithm is expressed in (1). This objective function is given to each control device. Entire system optimization is facilitated by each lighting fixture minimizing this objective function.

$$
\begin{aligned}
f &= P + w \sum_{j=1}^{n} g_j \qquad (1)\\
P &= \sum_{i=1}^{m} Cd_i \\
g_j &= \begin{cases} R_j(Lc_j - Lt_j) & (Lc_j - Lt_j) \geq 50 \\ 0 & 0 \leq (Lc_j - Lt_j) < 50 \\ R_j(Lc_j - Lt_j)^2 & (Lc_j - Lt_j) < 0 \end{cases} \\
R_j &= \begin{cases} v_j + r_j & r_j \geq threshold \\ 0 & r_j < threshold \end{cases} \\
v_j &= \begin{cases} 0.5 & the\ lighting\ ID\ is\ acquired \\ 0 & the\ lighting\ ID\ is\ not\ acquired \end{cases}
\end{aligned}
$$

$$
\begin{aligned}
&n: \ number\ of\ illuminance\ sensors \\
&m: \ number\ of\ lighting\ fixtures \\
&w: \ weight,\ v: \ ID\ acquisition\ state \\
&r: \ coefficient\ correlation \\
&P: \ electricity\ usage\ amount \\
&Lc: \ current\ illuminance \\
&Lt: \ target\ illuminance,\ Cd: \ luminance
\end{aligned}
$$

The proposed algorithm sets the design variable as the luminance and aims for the minimization of f in (1). f is obtained from $g(i)$, which expresses the illuminance difference between the current illuminance Lc and the target illuminance Lt, and electricity usage amount P. $g(i)$ is added if the illuminance difference is negative or is 50[lx] or more. That is to say, if the current illuminance falls below or above the target illuminance, light will be increased immediately. Sum of luminance Cd for each lighting fixture is used as electricity usage amount P. This is due to the supply voltage characteristic of fluorescent lamps with linear relationships between luminance and electricity usage amount. Weight w is multiplied to P. The option of prioritizing target illuminance optimization or electricity usage amount minimization is determined based on the value of w. v indicates the presence or absence of lighting ID acquisition, and r indicates correlation coefficient. This facilitates the utilization of benefits of both VLC and ANA/CC.

F. Neighborhood determination method

In ANA/CC+VLC, the luminance of each light is changed randomly with in a given range, and this range is called a neighborhood range in ANA/CC+VLC. As you can see in Fig.4, there are three types of neighborhood range in ANA/CC+VLC and it is used to generate next luminance. The values in Fig.4 shows the relative rate of each neighborhood size. These upper and lower values of neighborhood range is estimated experimentally. Neighborhood range A attaches the importance to lower the luminance from current luminance to converge to target illuminance. Neighborhood range B generates the next luminance equally in the upper and lower sides, and it is used to adjust the luminance. Neighborhood range C attaches the importance to increase the luminance intensity from current luminance. Only the neighborhood B has been used for the conventional control algorithm "SHC" so far. i is the illuminance sensor number.

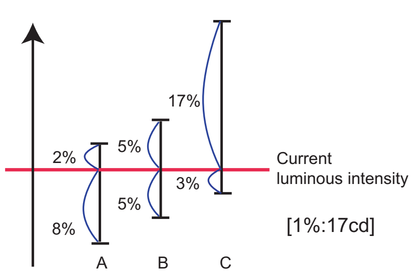


Fig. 4. Three neighborhood ranges

To select one of the neighborhood ranges adaptively, whether the lighting ID was acquired is used. Then next luminance is generated randomly with in the neighborhood range.

$$
\begin{cases}
A & R_i < threshold \\
B & R_i \geq threshold\ and\ Lt_i \leq Lc_i \\
C & R_i \geq threshold\ and\ Lt_i > Lc_i
\end{cases}
$$

i is illuminance sensor's number, Lt is target illuminance, and Lc is current illuminance.

The result of the optimum solutions obtained by the proposed optimization algorithm reaches occasionally a local optimum solution instead of the global one, because this algorithm is based on SHC. However, the neighborhood ranges used in this algorithm are so wide that the possibility of escaping from local optimum solutions becomes very high. Therefore, the final result seldom reaches a local optimum solution. Even if the result reaches a local optimum solution, the objective function values of the local optimum solutions are not so different from the one of global optimum solutions.

IV. Validation experiment using ANA/CC+VLC

A. Outline of experiment

We can perform the experiment of intelligent lighting system with the conventional algorithm ANA/CC in the experiment room. However, visible-light communication technology is not introduced into the real experiment environment yet. Therefore in this research, real space will be replicated with a computer. In addition, the difference between the results drawn by the simulator and the results obtained in the real experiment environment is very small [11].

The proposed algorithm will be applied, numeric experiments using ANA/CC+VLC will be conducted in the two experiment environments indicated below. We verified that the autonomous distributed experiment system can satisfy the target illuminance and minimize the electricity usage amount using ANA/CC+VLC. Also, it compares with the conventional algorithm ANA/CC in order to verify the proposed algorithm efficiency. The experiment environments are indicated in Fig. 5. The parameters for ANA/CC+VLC and ANA/CC used in the experiment are as stated on Table I. Furthermore, the illuminance of each illuminance sensor which is used in finding the objective function value will be calculated using the point method for straight-line light source.

- Experiment 1 : No change in environment
  The target illuminance for the installed illuminance sensors is set to 750[lx] for sensor 1, 650[lx] for sensor 2, and 550[lx] for sensor 3.
- Experiment 2 : Illuminance sensors are moved
  Illuminance sensor 3 is moved from its steady status in Experiment 1 to directly below lighting fixture 1.

B. Visible-light communication arrival range

It is possible that the arrival range of visible-light communication will change drastically based on luminance, because visible-light communication can only transmit information within the range that light shines. Therefore, 2 patterns are set

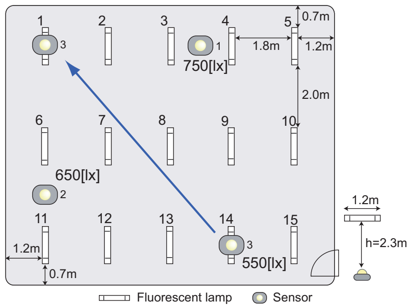
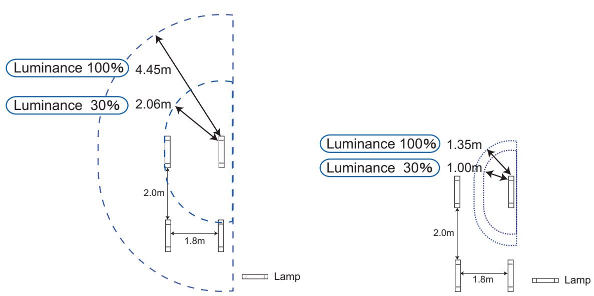


Fig. 5. Experiment environment

TABLE I
EXPERIMENT PARAMETERS

Kind of illuminant	Fluorescent lamp
Number of fluorescent lamps	15
Number of illuminance sensors	3
Target illuminance[lx]	750,650,550
Maximum luminance[cd(%)]	1700(100)
Minimum luminance[cd(%)]	510(30)
Initial luminance[cd(%)]	1700(100)
FOV of a receiver terminal[deg.]	70.0
Weight : w	10.0
Maximum threshold value for ANA/CC	0.5
Minimum threshold value for ANA/CC	0.3
Number of data	50

as indicated in Fig. 6 for the information of fluorescent lamp luminance and visible-light communication arrival range, and verification is to be conducted.



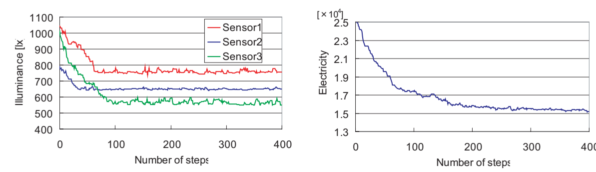
(a) Pattern-large (b) Pattern-small

Fig. 6. Visible-light communication arrival range

In Pattern [large], the visible-light communication arrival range is set widely, in such a way as to facilitate acquisition of the lighting ID for 6 closely placed fixtures when the minimum luminance is 30%. Conversely, in Patten [small], visible-light communication arrival range is set at a distance allowing reception of the lighting ID of 4 nearby fixtures when maximum luminance is 100%, and at a distance assumed to allow reception of the lighting ID of 2 nearby fixtures when minimum luminance is 30%. Furthermore, the numeric values indicated in Fig. 6 are calculated via fluorescent lamp emission angle, and luminance and emission angle share a proportional relationship. Experiment 1 was conducted applying the proposed algorithm for each of these 2 visible-light communication arrival range patterns. For each pattern the optimal lighting pattern was achieved, and it was clear that if each illuminance sensor converges on the target illuminance, the proposed algorithm can adapt regardless of the visible-light communication arrival range.

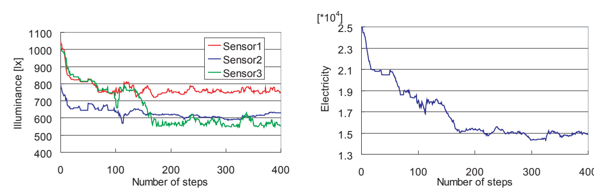
C. Result of the experiment using ANA/CC+VLC

1) Experiment 1 — visible-light communication range Pattern [large]: The illuminance and electricity usage amount history for setting at visible-light communication arrival range Pattern [large] are indicated on Fig. 7. Also, for the purpose of comparison, the experiment results using ANA/CC are indicated on Fig. 8.



(a) Illuminance history (b) Electricity history

Fig. 7. Experiment Results (Pattern [large])



(a) Illuminance history (b) Electricity history

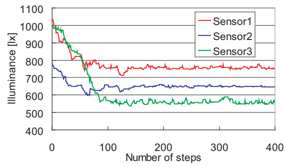
Fig. 8. Experiment Results (ANA/CC)

From Fig. 7(a) it is clear that after experiment commencement, the illuminance of illuminance sensors 1, 2, and 3 at approximately 100 steps were 771, 652, and 568 [lx] respectively, and illuminance was converging on the target illuminance. Also, Fig. 7(b) indicates that as the search progresses, electricity usage amount minimization is occurring.

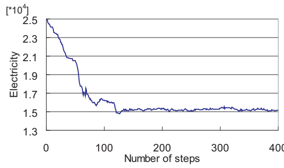
Also, pertaining to the comparison between the proposed algorithm and ANA/CC, it is clear that the proposed algorithm achieves approximately equal results.

2) Experiment 1 — visible-light communication range Pattern [small]: The illuminance and electricity usage amount history for setting at visible-light communication arrival range Pattern [small] are indicated on Fig. 9, in the same environment as in Fig. 5. The parameters used are the same as Table I.

It is clear that with the improved algorithm illuminance sensors 1 and 3 are converging and they are in a state of nearly fulfilling the target illuminance after the sensors go through approximately 120 steps. Also, in Fig. 9(b), electricity usage amount minimization is occurring at nearly the same state as ANA/CC.



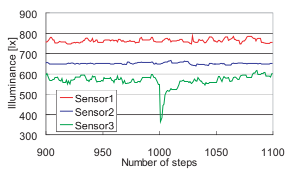
(a) Illuminance history



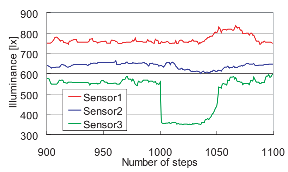
(b) Electricity history

Fig. 9. Experiment Results (Pattern [small])

3) Experiment 2: Using ANA/CC+VLC, Experiment 2 was conducted, and the effectiveness of the ability to respond to changes in environment was verified. Fig. 10(a) indicates the individual illuminance sensor illuminance and electricity usage amount history.Also, for the purpose of comparison, the experiment results using ANA/CC are indicated on Fig. 10(b).



(a) ANA/CC/VLC



(b) ANA/CC

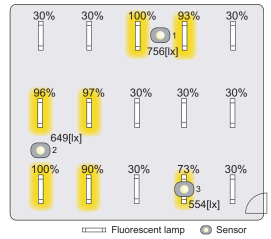
Fig. 10. Experiment Results (illuminance)

From Fig. 10(a), it is clear that when illuminance sensor 3 was moved (at 1000 number of steps), the illuminance of sensor 3 was largely lower than the target illuminance, but after that it shot up, and at approximately 15 steps it was able to achieve the target illuminance. Also, from Fig. 10(b), in ANA/CC the illuminance of sensor 3 achieved the target illuminance at approximately 55 steps.

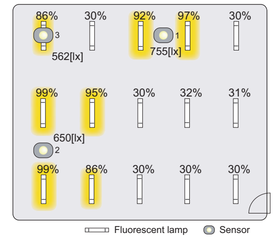
The luminance states acquired directly before and after moving sensor 3, by approximately 2000 steps, are indicated on Fig. 11(a) and Fig. 11(b) respectively. The final illuminance of the individual illuminance sensors were 755, 650, and 562 [lx], converging near the target illuminance. Comparing Fig. 11(a) and Fig. 11(b), lighting fixture 1 luminance was increased after illuminance sensor 3 was moved closed to lighting fixture 1 location, and since lighting fixtures 13 and 14 no longer have an effect on illuminance sensors, the luminance of them decreases. Based on these experiment results, it is clear that the system is able to respond to illuminance sensor movement.

V. Conclusion

Intelligent lighting system which can contribute to energy saving, and which can provide the desired illumnance to desired location based on the information from movable illumiance sensors was proposed. In this research, we proposed the intelligent lighting system using visible-light communication and the new control method called ANA/CC+VLC.



(a) Before movement



(b) Conclusive state

Fig. 11. Luminance

This algorithm make the convergence to the preset target illuminance accelerated. The effectiveness in proposed system was examined, and the effectiveness was verified via numeric experiments using a simulator. It was confirmed that this algorithm facilitates a quick switch to an energy conservation state wherein lighting fixtures with illuminance sensors nearby shine brightly, and lighting fixtures with no illuminance sensor shine weakly. Also, regarding the conventional algorithm, this proposed algorithm responds instantaneously even to environment changes. Based on the above, the algorithm can be considered extremely efficient as an intelligent lighting system control algorithm.

References

[1] T.Kawaoka M.Miki. Design of intelligent artifacts:a fundamental aspects. *Proc.JSME Inter-national Symposium on Optimization and Innova-tive Design(OPID97)*, 1997.

[2] CHAN ALS LAM JC. Energy audits and surveys of air-conditioned buildings. *Proceeding of Australian and New Zealand Architectural Science of Association Conference, University of Canberra, Australia*, pp. 49–54, 1995.

[3] Lighting controls. *Int Light Rev*, Vol. 49, No. 981, pp. 48–49, 1998.

[4] RUBINSTEIN F PETERSON D. Effective lighting control. *LD+A*, Vol. 13, No. 2, pp. 18–23, 1983.

[5] RUBINSTEIN F. 50 percent energy savings with auutomatic lighting controls. *Strateg Plann Energy Environ*, Vol. 11, No. 2, pp. 17–31, 1991.

[6] WILKINSON MA. The effect of glazing upon energy consumption within buildings. *Lighting Research and Technology*, Vol. 24, No. 2, pp. 99–101, 1992.

[7] P.J.Littlefair. Predicting lighting energy use under daylight linked lighting controls. *Building Research and Information*, Vol. 26, No. 4, pp. 208–220.

[8] TA.Heasman AI.Slater, WT.Bordass. People and lighting controls. *BRE information paper IP 6/96, Garston: CRC*.

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

[10] Imazato K Miki M, Hiroyasu T. Proposal for an intelligent lighting system and verification of control method effectiveness. *Proc IEEE CIS*, pp. 520–525, 2004.

[11] Imazato K Yonezawa M Miki M, Hiroyasu T. Intelligent lighting control using correlation coefficient between luminance and illuminance. *Proc IASTED Intelligent Systems and Control*, Vol. 497, No. 078, pp. 31–36, 2005.

[12] Masao Nakagawa Toshihiko Komine. Integrated system of white led visible-light communication and power-line communication. *IEEE Transactions on Consumer Electronics*, Vol. 49, No. 1, pp. 71–79, 2003.

[13] Tiffany K.Buffaloe Deron K.Jackson and Steven B.Leeb. Fiat lux : A fluorescent lamp digital transceiver. *IEEE Transactions on industry applications*, Vol. 34, No. 3, pp. 625–630, 1998.