INTELLIGENT LIGHTING CONTROL USING CORRELATION COEFFICIENT BETWEEN LUMINANCE AND ILLUMINANCE

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

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

Kazuhiro Imazato and Motoi Yonezawa
Graduate School of Engineering
Doshisha University
Kyoto Japan
email: kimazato@mikilab.doshisha.ac.jp

ABSTRACT

An intelligent lighting system which provides required illumiancne at an appropriate location is proposed. This system does not have the centralized control device and also it is controlled by each intelligent lighting's autonomous operation. Also the intelligent lighting system can contribute to energy saving. In this research, a new algorithm is proposed. For rapid converges it uses the correlation coefficient between the illuminance at given locaion and the luminance of each light . We actually construct an autonomous distributed experiment system and verification tests were conducted using the proposed control method. The results showed that the various illuminance sensors converged to the preset target illuminance. We also confirmed that the algorithm can respond adaptively to environmental changes and it is effective to energy saving.

KEY WORDS

Intelligent, lighting systems, autonomous distributed control, energy saving, intelligent system, cofficient crrelation.

1 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 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][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 photo-electric 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. On the other hand, a new lighting system called intelligent lighting system, which can resolve these problems, is proposed. We used an autonomous distributed optimization algorithm, based on the stochastic hill climbing method, as the lighting control method before. This control method is useful for environments with less than some ten lightings. However, the convergence of illuminance to target illuminance becomes very slow. Therefore, it is assumed that the estimation of distance between light and illuminance sensor can improve the speed of convergence. The distance can be estimated from the correlation coefficient between the luminance of the light and the illuminance mesured by illuminance sensor. To realize advanced intelligent lighting system, the algorithm which controls the system is important as well as the completeness of the hardware. In this research, a new control algorithm, which is based on the concept of autonomous distributed control, using correlation of illuminance and luminous intensity is proposed.

2 What is an intelligent lighting system?

2.1 Overview of intelligent lighting system

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

2.1.1 Autonomous distributed control

In the 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 high reliability can be achieved even in large-scale buildings.

2.1.2 Achieving autonomous lighting control

In today's illumination systems, only the limited lighting pattern can be realized due to the wiring pattern. However, with the intelligent lighting system, it is possible to realize an arbitrary lighting pattern which is not dependent on the wiring of lights. Also this intelligent lighting system, the user simply sets the target illuminance, and the system can automatically determine the necessary luminance, without making the user aware of the location of lights, and thus can provide the appropriate illuminance to the appropriate location.

2.2 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.1 shows the configuration of an intelligent lighting system.

2.3 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.
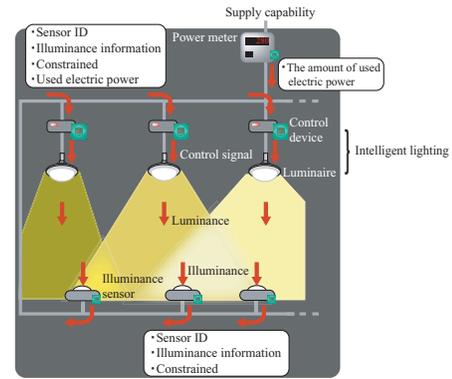

Figure 1. Configuration of the intelligent lighting system

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 illuminance and current illuminance of each illuminance 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.

6. By repeating Steps 2 to 5, the system constantly senses environmental information, and provides control so that goal is satisfied.

Using the above process, each inteligent light can 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.

3 The configuration of autonomous distributed experiment system

The autonomous distributed experiment system, is actually built based on intelligent lighting systems concept. The configuration of the experiment system is 15 inverter controllable fluorescent lights, 15 lighting control devices, multiple movable illuminance sensors. Inverter control is a technology wherein luminance is adjusted by arbitrarily varying the duty ratio of a digital waveform. All of these hardware are connected to one network. In this experiment system the power meter, which measures the amount of used electricity is not included. The sum of each light's

luminance intensity is substituted as the amount of used electricity. In addition, in this experiment system there is no central control element with controls over the entire system. Each light has it's own lighting control device so this can achieve the autonomous distributed control system.

4 Adaptive Neighborhood Algorithm using Correlation Coefficient

In this chapter, new algorithm that can search effectively by estimating the distance of the light and the sensor from the correlation between luminance and illuminance intensity, is proposed.

4.1 Overview of adaptive neighborhood algorithm using correlation coefficient

The proposed algorithm calculates the correlation from "the amount of luminous intensity changed" and "the amount of illuminance intensity changed". From now on, proposal algorithm is called Adaptive Neighborhood Algorithm using Correlation Coefficient as ANA/CC. The flow chart of this algorithm is shown in Fig.2.
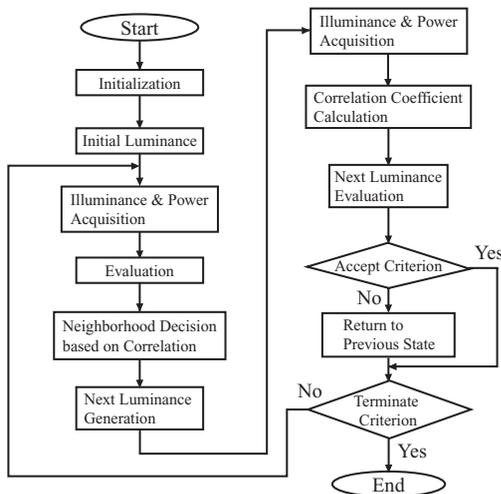

Figure 2. Adaptive Neighborhood Algorithm using Correlation Coefficient

The control process of this algorithm is shown below.

1. Perform initialization and set the initial parameters.

2. Switch on all fluorescent lights at their initial luminance.

3. Calculate the objective function from information of each illuminance sensors (Sensor ID, current illuminance, and target illuminance) and amount of electricity used.

4. An appropriate neighborhood range is determined based on the correlation.

5. Next luminance is generated randomly with in the neighborhood, which is determined at (4), and turn on each light with the new luminance.

6. Get new information of illuminance sensors and new amount of electricity used.

7. Calculate the correlation from the new illuminance and new luminance.

8. Calculate the objective function from new illuminance and amount of electricity using.

9. If the objective function value is satisfactory, set that luminance and return to step (3).

10. If the objective function value worsened in step (8), cancel the privius of luminance and retrun to step(3).

By performing the above operation, it can converge to the target illuminance and to a power saving state.

4.2 Further details about ANA/CC

4.2.1 Correlation between luminance and illuminance

In order to converge to the target illuminance and minimize electric power in short time, estimating the distance of lights and illuminance sensors is thought to be effective in lighting control algorithm. In proposed algorithm a correlation coefficient is used to estimate the distance autonomously and dynamically. The amount of luminance changed and the amount of illuminance changed is used to calculate the correlation. In other word, "the difference between current luminance and next luminance" and "the difference between the current illuminance and next illuminance" is used to calculate correlation coefficient. This will enable us to estimate the distance correctly.

4.2.2 About a correlation coefficient and a distance

Fig.3 shows the example of the distance of lights and illuminance sensors. For light 1, the correlation with sensor A becomes high and the correlation with sensor B is low . For light 2, the correlation with sensor A becomes low, and the correlation with sensor B is high. For light 3, the correlation with both sensors becomes low because they are at the distant position from light 3. If the distance can be estimated by the correlation correctly, lights which does not have sensor in near distance should lower the luminance. And lights which have sensors in near distance should change the luminance to appropriate luminance intensity to satisfy the target illuminance.
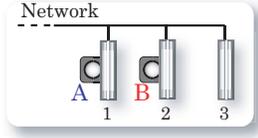
Figure 3. Position between lamps and sensors

4.2.3 Three types of changes in luminance

In ANA/CC, the luminance of each light is changed randomly with in a given range, and this range is called a neighborhood range in ANA/CC. As you can see in Fig.4, there are three types of neighborhood range in ANA/CC 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 value 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 so far.
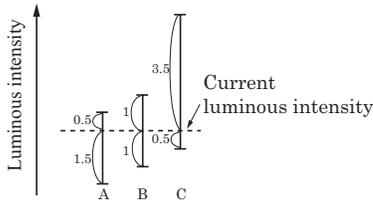

Figure 4. Three neighborhood ranges

4.2.4 Determination of neighborhood range process

In ANA/CC there are three types of neighborhood range as shown in Fig.4. To select one of the neighborhood ranges adaptively, the correlation coefficient between luminance and illuminance is used. Then next luminance is generated randomly with in the neighborhood range. The process of the determination of neighborhood range is shown below.

1. Each light calculates the correlation coefficient with all the illuminance sensors in the room.

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

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

2. If all the correlation coefficients are less than the threshold, neighborhood range A is selected. If more than one correlation coefficient is higher than the threshold and the values of all the sensors current illuminance are higher than the target illuminance, neighborhood B is selected. If more than one correlation coefficient is higher than the threshold and more than one current illuminance of the sensor are less than the target illuminance, neighborhood range C is selected. The value of the threshold is determined by pre-experiment.

From these rule, the lights which have the illuminace sensors in near distance should change the luminance properly for that sensor and the light which does not have illuminance sensor in near distance should decrease the luminance to minimum luminance.

4.2.5 Objective function used in this algorithm

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.

$$\begin{aligned} f &= P + w\sum_{j=1}^{n} g_j & (1)\\ P &= \sum_{i=1}^{m} Cd_i \\ g_j &= \begin{cases} 0 & (Lc_j - Lt_j) \geq 0 \\ R_j(Lc_j - Lt_j)^2 & (Lc_j - Lt_j) < 0 \end{cases} \\ R_j &= \begin{cases} r_j & r_j \geq Tmin_j \\ 0 & r_j < Tmin_j \end{cases} \end{aligned}$$

In ANA/CC, the goal is to minimize f in Equation.1. f is the sum of g_j, which indicates the illuminance difference between the current illuminance Lc and target illuminance Lt, and P is the amount of electric power used. r indicates correlation coefficient, and $Tmin$ is the minimum value of threshold. For electric power P, use the sum of each lighting's luminance intensity Cd. The luminance has a linear relationship with the energy consumed, and here it is taken to be the power used by each light. g_j is added only if the illuminance difference is negative. In other words, the light increase the luminance rapidly if the current illuminance is less than the target illuminance. If

the correlation is less than the minimum threshold, multiply 0 to the illuminance difference. It is thought that the accuracy will improve to satisfy the target illuminance, by narrowing-down the optimization target to high correlation sensor (sensor close to the light). In addition, this g_j is multiplied by weight w. the value of this weight determines whether priority will be placed on optimizing target illuminance, or optimizing electric power.

5 Validation experiment using ANA/CC

5.1 The outline of an experiment

Experiments were conducted using the 3 pattern indicated in Fig.5, and we verified that the autonomous distributed experiment system can satisfy the target illuminance and minimize the electric power using ANA/CC. Also we verified that ANA/CC can estimate the distance of light and illuminance sensor from the correlation.

The parameters used in the experiment are shown in Table.1.
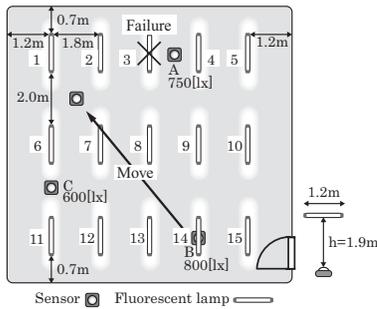
Figure 5. Experiment environment

Table 1. Experiment parameters

Number of fluorescent lamps	15
Number of illuminance sensors	3
Target illuminance [lx]	750 800 600
Distribution of light increase decrease(Pattern A) [%]	+2,+1,0,-1,-2,-3, -4,-5,-6,-7,-8
(Pattern B) [%]	$\pm5,\pm4,\pm3,\pm2,\pm1,0$
(Pattern C) [%]	+17,+16,+15,$\cdots$ +1,0,-1,-2,-3
Maximum luminous [%]	100
Minimum luminous [%]	30
Initial luminance [%]	100
Weight(w)	1.0
Maximum threshold value	0.5
Minimum threshold value	0.3
Number of data for the correlation coefficient	50

- **Experimetn1**   When the environment is fixed
  The target illuminance of the illuminance sensor was set to: 750[lx] for sensor A, 800[lx] for sensor B, 600[lx] for sensor C. The arrangement of illuminance sensor is shown in Fig.5.

- **Experiment2**   When the illuminance sensor is moved
  The illuminance Sensor B is moved from its sate in Experiment1 to the center position between Lights1, 2, 6, and 7.

- **Experimetn3**   When the intelligent lighting is malfunctioned
  Light3 is made to fail in the sate in Experiment1.

5.2 Result of the experiment using ANA/CC

5.2.1 Experiment1 When the environment is fixed

This section describes the experiment result when the environment was fixed. Fig.6, Fig.7, and Fig.8 shows the history of illuminance at each illuminance sensor, the electric power, luminance of light4, 6, 9, 12.
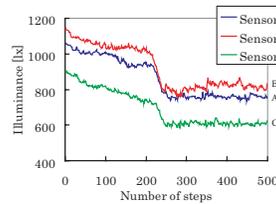

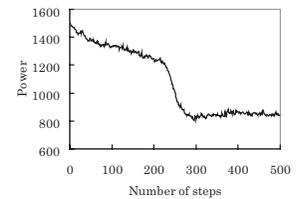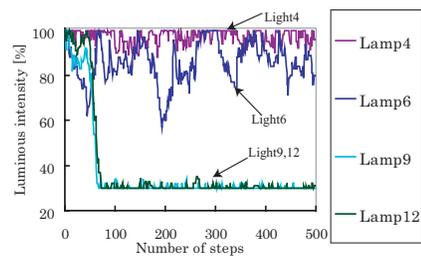Figure 6.   Illuminance history

Figure 7. Power history

Figure 8. Luminous intensity history

As you can see from Fig.6, after the start of the experiment, the initial illuminance decreases and when the number of searching step is 250(2 minute), the illuminance at illuminance sensors A, B, and C becomes, 776, 792, 597[lx], so the illuminance converges to the value close to the target illuminance. As you can see in Fig7, as search proceeds the electric power decreases. From Fig.8, the luminance of

light 4, and 6 are high because they are at the near distance of illuminance sensor. The luminance of light 9, and 12 are at minimum luminance because they don't affect any sensor.

Fig.9-a and Fig.9-b shows the history of correlation coefficient of the light 4 and 9. Sensor A is near the light 4 and the sensor does not exist near the light 9. Fig.9-a, shows that only Sensor A's correlation coefficient is at high value. Fig.9-b shows that correlation coefficient is low for all three sensors. In other words, the result of correlation coefficient between luminance and illuminance can estimate the distance of the lights and the illumiance sensors.
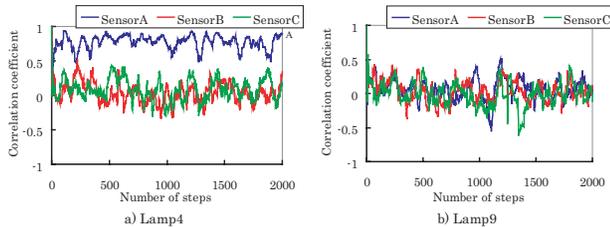
Figure 9. Correlation coefficient between the lamp and the sensors

The final state of this experiment, when the searching step is 2000(after 1 hour), is showed in Fig.10. The illuminance at each sensor is 759, 791, and 613[lx], so it converges to a value close to the target illuminance. Also, only the lights which have the sensor in near distance are lighted strongly, and the lights which does not affect any of the sensor are lighted with minimum luminanse. From these result, we confirm that the power saving state is obtained by ANA/CC.
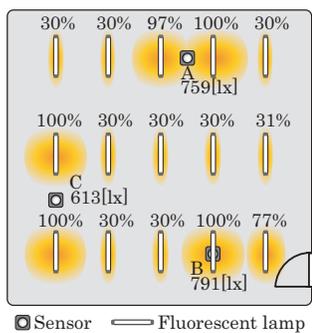

Figure 10. Luminous intensity[%] and illuminance in the stady state

5.2.2 Experiment2: when the sensor is moved

This section describes the experimental result when the illuminance sensor was moved. Fig.11 show the history of
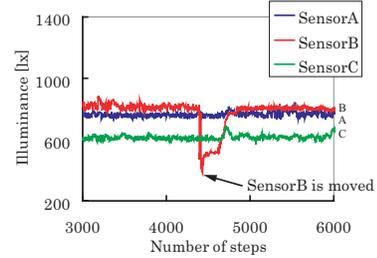
illuminance for each illuminance sensor.

Figure 11. Illuminance history

In Fig.11, the value of illuminance sensor B, when it is moved (i.e. when the number of steps is 4400), is much less than the target illuminance. This happened because sensor B is moved to the darker location of the room. However, after about 400 steps (3 minute) the illuminance of illuminance sensor Breach backs to the target illuminance.
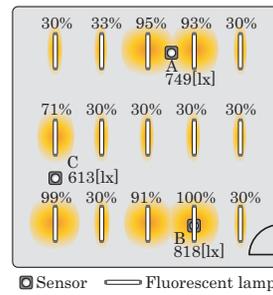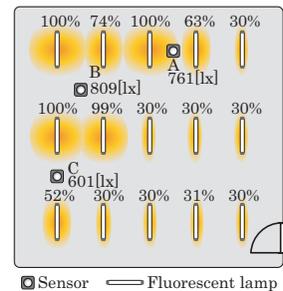

Figure 12. Before sensorB moved

Figure 13. Steady state

Fig.12 shows the luminance[%] before the movement of sensor B and Fig.13 shows the steady state after sensor B is moved (about 1000 steps after the movement). In the steady state, the illuminance of each sensor becomes 761, 809, 600[lx] so the algorithm has almost converged on the target illuminance. By comparing Fig.12 and Fig.13, we can see that luminance was increased at light 1, 2, 6, and 7(at the location where sensor B is moved to), and the luminance of light 13, and 14 dropped because they no longer affect any illuminance sensor. From this experiment results, ANA/CC can respond to movement of illuminance sensor.

5.2.3 Experiment3: when the light 3 malfunctions

This section describes the experimental result when the light 3 malfunctions. Fig.14 show the history of illuminance for each illuminance sensor.

As you can see in Fig.14, when the light 3 malfunctioned, the illuminance of sensor A dropped to 470[lx] and
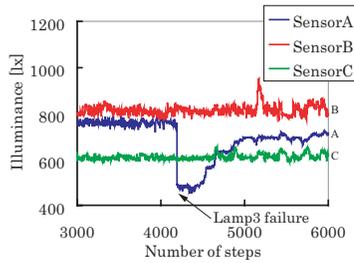
Figure 14. Illuminance history

after about 800 steps (6 minute) from the malfunction the illuminace of sensor A reach to 700[lx]. However, it does not reach to 750[lx] which is the target illuminance. This is because the influence of light 3 was too big, so it could not satisfy the target illuminance even the lights that are in near distance of the sensor A lighted up with the maximum luminance intensity.
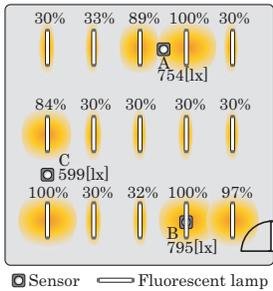
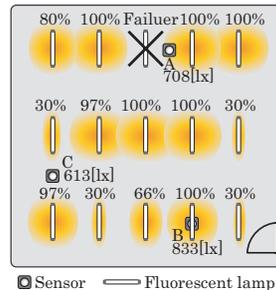

Figure 15. Before the lamp3 failure

Figure 16. Steady state

Fig.15 and Fig.16 shows the state before the light 3 malfunction and the steady state about 1000 steps after malfunction occurred. In the steady state, the illuminance of each sensor becomes 708, 833, and 613[lx] so ANA/CC almost converged on the target illuminace except sensor A. Comparing Fig.15 and Fig.16, we see that the luminance of lights 1, 2, 5 ,7, 8 and 9 increased to compensate for the brightness of light 3. From this results, we can see that the entire system tries to compensate the brightness of malfunctioned light.

6 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 new control method called ANA/CC. This algorithm calculates the correlation coefficient from luminance and illuminance to estimate the distance between the light and the illuminace sensor. Also we construct autonomous

distributed experiment system and tests were conducted using the proposed algorithm. The result showed that the light which are in near distance of the illuminance sensor lighted up with appropriate luminance and the lights which does not affect any of the sensors lighted up with minimum luminance. The results of the experiments showed that ANA/CC can operate appropriately. For these reasons, we confirm that ANA/CC is very effective control method for the intelligent lighting system.

References

[1] MIKI M, KAWAOKA T   Design of Intelligent Arti-facts:A Fundamental Aspects *Proc.JSME International 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 Intelligent 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.*

[11] Miki M Hiroyasu T Imazato K *Proposal for an Intelligent Lighting System, and Verification of Control Method Effectiveness* Proc IEEE CIS, Page520-525, (2004)