LETTER

Design of an Energy-Aware LED Light System (EA-LLS) for Energy Saving and User Satisfaction through Daylight, Space and User Movement Analysis in Buildings

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SUMMARY This letter introduces an Energy-Aware LED Light System (EA-LLS) that provides adequate illumination to users according to the analysis of the sun's position, the user's movement, and various environmental factors, without sun illumination detection sensors. This letter presents research using algorithms and scenarios. We propose an EA-LLS that offers not only On/Off and dimming control, but dimming control through daylight, space, and user behavior analysis.

key words: *energy saving, user satisfaction, energy aware, daylight analysis, space analysis, user movement analysis*

1. Introduction

There have been many efforts to develop building control systems for energy saving. One of these efforts is a building light control system that analyzes the amount of light entering a building. The amount of light entering a building depends on a variety of factors, such as the purpose of the building, building location, number of windows, sizes of windows, effects from the surrounding buildings, and local weather conditions. However, although the amount of light entering a building varies according to the architecture of the building, lighting has the same brightness in both bright places and dark places.

To solve this problem, existing studies have proposed a system to control lighting by using an illuminance light sensor. However, there are two difficulties in control by illuminance sensor. First, it is hard to determine the sensor position for daylight detecting. Second, the cost of installing these sensors at different locations are expensive. In this letter, we will attempt to research a way to increase energy performance and user satisfaction of a building's light through analysis of the daylight influence factor, and a user's movement, without using an illumination sensor. Daylight analysis and modeling has several advantages that include enhancing the use of a space environment, managing the affiliated energy loss/gain, the use of energy, and so on [4]. This letter proposes a building LED system that not only offers On/Off and dimming control, but also 3 modes energy-aware control by the analysis and modeling of daylight, building structure, location of the sun, and users.

Manuscript received June 18, 2014.
Manuscript revised November 27, 2014.
Manuscript publicized July 17, 2015.

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DOI: 10.1587/transinf.2014EDL8124

2. Related Works

There are many research papers about the intelligent LED lighting systems in a building environment for energy saving and user satisfaction. Tan *et al* [1] proposed a smart DC LED lighting system through the wireless sensor network (WSN). The proposed system shows a personal lighting management strategy using occupant task algorithm that operates according to time and user activities. Pandharipande *et al* [2] proposed illumination rendering LED light system from present daylight and user preference for energy saving and user satisfaction. This paper shows that LED light control algorithms that applied centralized/distributed methods. Miki *et al* [3] proposed an intelligent lighting system for worker's comfort and energy efficiency. This paper shows the brightness distribution method that provides optimal brightness for users and a brightness ratio through user's environment. But in our paper, we assumed that there are no illumination sensors, and we focused on controlling light through the energy modeling using the modeling of the sunlight/space/user based on energy-awareness and context-awareness.

3. Daylight Modeling in Energy-Aware LED Light System (EA-LLS)

Figure 1 shows the daylight components, space, and user's behavior in building. Daylight components are the light entering a building by its origin - directly from the sun light or by reflection [5]. As in Fig. 1, the light entering a building depends on many factors, including room location, room size, window glass transmittance, window shades, and window size [6]–[8].

So the light entering each room is affected by the many external influence factors mentioned above. Our proposed lighting system is controlled depending on the characteristics of the each room, because the daylight influence fac-

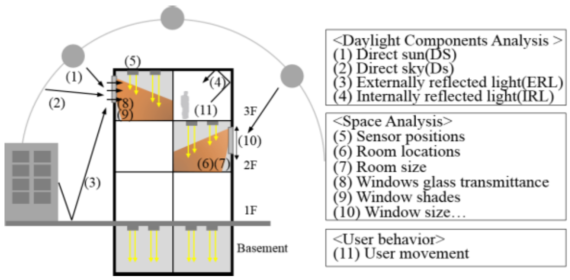

Fig. 1 Components of daylight and daylight influence factors [5]

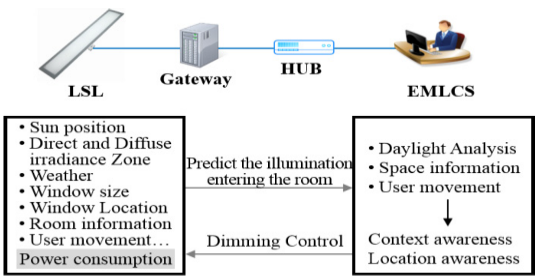

Fig. 2 System overview of the EA-LLS

tors entering each room are different. Figure 2 shows an overview of the EA-LLS that consists of an Energy Management and LED Control Server (EMLCS) and LED System Light (LSL). The EMLCS predicts the daylight illuminance level, through analysis of the above-mentioned daylight factors that change according to the movement of the sun [4].

In addition, for user-friendliness and energy efficiency, the EMLCS controls the LSL through the movement of cars, and patterns of user movement. The LSL receives the user location information through the motion sensor, and then it sends the sensing information to EMLCS. Thereafter, EMLCS sends the illuminance control signal to the LSL. It also collects information and classification tasks through the context aware module, and stores the information in a database. The main features of our system are as follows:

- Energy loss/gain management for energy efficiency of the LED light in a space that is directly or indirectly affected by sunlight.
- Intelligent grouping control, according to the situation.
- Prediction of illuminance levels through daylight, space information, and user pattern analysis.

4. System Design and Implementation

4.1 System Architecture:

4.1.1 Energy Management and LED Control Server (EMLCS)

Figure 3 shows the EMLCS and LSL system architecture. The EMLCS determines the present situation by information gathering, and information modeling, so it can increase the efficiency of building energy, through prediction of the illuminance levels in a space.

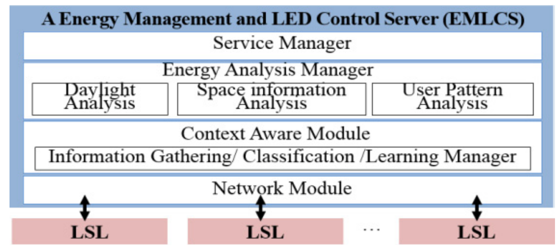

Fig. 3 System architecture

Energy Analysis Manager (EAM):

- Daylight Analysis Module (DAM): Determines the daylight illuminance level through the collection of daylight factors. Analyzes the sensing information collected from the each sensor, and predicts the degree of LSL illumination.
- Space Information Analysis Module (SIAM): Analyzes the information of sensor positions, room locations, room size, windows glass transmittance, window shades, and window size.
- User Movement Analysis Module (UMAM): This module analyzes movements of the user, and determines their patterns.

Context Manager (CM):
The CM determines the present situation through the analysis of context information. The Context Manager has a rule that gathers the contexts by Information Gathering/ Classification Learning Manager (IGCLM), using the context model. IGCLM has a rule that collects and classifies the information. It also learns through analyzing the past data [9].
Service Manager (SM):
The SM enables an energy service management process that collects and manages environmental information, in order to provide adequate illumination to users.
Network Manager (NM):
The NM module manages communication between the EMLCS and LSL.

4.1.2 LED System Light (LSL)

Motion sensors in the LSL detect user movements. They transmit the user movement information to the EMLCS, and receive dimming control information.

4.2 Three Group Illuminance Control Algorithm

Figure 4 is an optimization control algorithm of the LSL and EMLCS. This system has three modes as below Table 1. The control variables for the system are as follows:

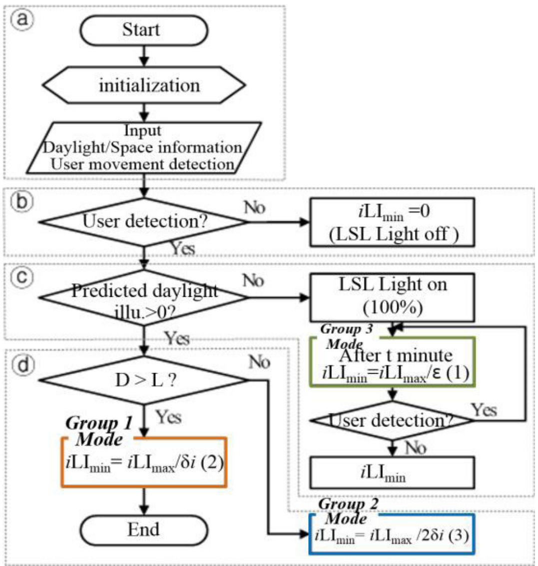

Fig. 4 EA-LLS control algorithm with 3 modes (3 group)

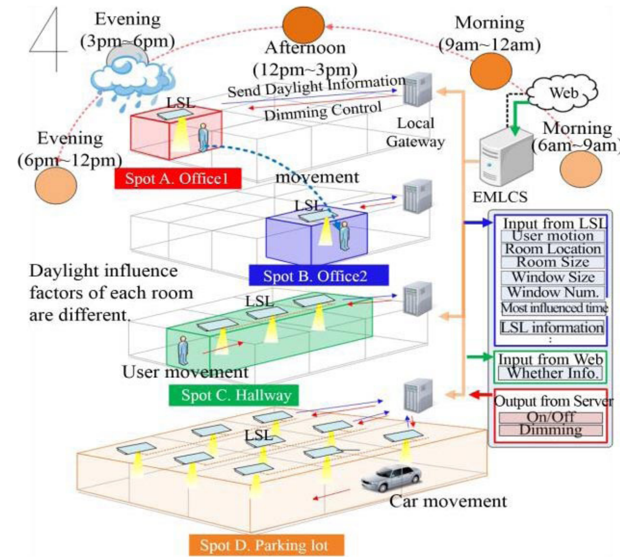

Fig. 5 EA-LLS control scenario

Table 1 Three LSL control group modes according to situation in EA-LLS (H: High, M: Middle, L: Low, FUM: frequency of user movement)

Group Mode	Situation				LSL control
	D:L	Affect of sunlight	FUM *	Space	
Mode 1	D ≥ L	H	H	Working area	Dimming control through the sunlight
Mode 2	0 < D < L	M	M	Hallway, Stairwells	Dimming control through the sun-light/user Movement
Mode 3	D = 0	No affect	L	Basement, Parking lot, Machine room	Dimming control through the sun-light/user Movement

δi	Daylight influence factor in space i (δo: in office, δh: in hallway)
D	Ratio of daylight
L	Ratio of each room LED light
ε	Optimum illuminance factor
iLImin	Minimum LSL illuminance in space i (oLImin: in office, hLImin: in hallway)
iLImax	Maximum LSL illuminance in space i
iLIe	LSL illuminance when an event occurs in space i
iLIp	LSL illuminance in space i

Table 1 shows the LSL energy-aware control (EAC) group modes according to the situation in EA-LLS. And operating flow is as follows.
ⓐ LSL receives the user movements by using a motion sensor.
ⓑ The LSL's motion sensor detects the movements of the user, and when the sensor does not detect user movement, the LSL light is kept off.
ⓒ If user motion is detected, the brightness of the LSL light is changed, depending on the degree of daylight influence factor. (ⓓ) EMLCS predicts the daylight illuminance through the daylight and Space information. When the predicted daylight illuminance entering the room is zero, LSL maintains a constant illuminance of 100%, and changes the illumination to LImin after t minutes, by using the formula below:

$$i\text{LImin} = i\text{LImax}/\varepsilon \qquad \text{(mode 3)} \qquad (1)$$

Then if a user motion is detected, the LSL light adjusts the brightness of the light to 100%. Whenever user movement is detected, LSL is controlled by formula (1). In this case, the formula is applied to a space where sunlight does not come in, as in an enclosed parking structure.
ⓓ If the predicted daylight illuminance > 0, LSL is controlled based on the percentage of the LED light and the daylight. For example, for office1 or office2, which are most influenced in the daylight time, if the ratio of each room light (L) is less than or equal to the ratio of daylight (D), LSL is controlled by the formula below.

$$i\text{LImin} = i\text{LImax}/\delta i \qquad \text{(mode 1)} \qquad (2)$$

But in areas such as a hallway, if the LED light ratio is greater than or equal to the daylight, LSL is controlled by the formula (3).

$$i\text{LImin} = i\text{LImax}/2\delta i \qquad \text{(mode 2)} \qquad (3)$$

4.3 LSL and EMLCS Control Scenario:

Figure 5 shows the control scenario of the proposed building LED light system. It also shows the optimized LED light control scenario of the LSL and EMLCS. Table 2 shows the value of D:L that is decided from space information.

D:L is the ratio between the influence of daylight and each room's LED light, when the amount of lights the user is satisfied with is 10, according to the time that a person gets up in the morning and goes to bed at night. The ratio of influence of sun light depends on the season. Table 3

Table 2 Space information and D:L* in scenario (D: Ratio of the amount of daylight, L: Ratio of the amount of LED light, MIT: Most influenced time of the daylight, nW/WS: Number of Window/Window Size (m × m), RL: Room Location, WR: Window Location, nLSL: Number of LSL)

Spot	MIT	nW/WS*	Room size(m×m)	RL/WL	nLSL*	D:L*
A	PM10~ PM17	3/1.5×2.5	4×8	West/West	2	5:5
B	AM09~ AM15	1/1.5×2.5	4×6	East/East	2	5:5
C	AM06~ PM18	-(Affected from other side)	3×20	Center of floor/North	3	2:8
D	-	-	15×20	Basement/-	6	0:10

Table 3 Ratio of the D:L is affected by the time and spot. (The influence of sunlight is dependent on the season. The D:L value is changed by seasonal variations.)

Spot \ Time		8	9	10	11	12	13	14	15	16	17	18
A	D	2	4	5	7	8	9	9	9	7	5	2
	L	8	6	5	3	2	1	1	1	3	5	8
B	D	3	5	8	9	9	9	7	6	4	3	1
	L	7	5	2	1	1	1	3	4	6	7	9
C	D	0	0	1	2	1	2	1	1	1	0	0
	L	10	10	9	8	9	8	9	9	9	10	10
D	D	0	0	0	0	0	0	0	0	0	0	0
	L	10	10	10	10	10	10	10	10	10	10	10

Table 4 The optimum illuminance level according to space and user behavior. (The following materials are referred to IESNA Lighting Handbook.) [10]

Space(Related Spot)	Behavior/ feature	Foot-candles(fc)	Lux(lx)
Administrative office(A/B)	reading/writing tasks	50	500
Computer Lab(A/B)	Keyboards	30	300
	Monitors	3	30
	Reading tasks	50	500
Drafting Room(A/B)	Drafting	75	750
Hallway(C)	Horizontal	30	300
	Vertical	15-30	150- 300
Stairwells(C)	Climbing the stairs	15	150
Parking Garage(D)	Parking	10–20	100-200

shows the change of D:L value according to the time and spot. Weather information is gathered from the web. The system control scenario is as follows: When the motion sensor detects the movement of the user, the LSL light is turned on. If the predicted daylight illuminance in EMLCS is greater than 0 (in Fig. 6, at 8am in the office), the LSL are controlled by formula (2) and (3), and if the predicted daylight illuminance is 0, the LSL are controlled by formula (1).

As in Fig. 6, if the sun rises, LSLs are controlled depending on the daylight influence factor (δ) and LSLs decrease illuminance according to optimum illuminance level mentioned Table 4. There are three modes of EA-LLS that operate dimming control through the sunlight and user movements in control scenarios.

Group_Mode 1: In Fig. 6 the LSLs in office1 (Spot A) and office2 (Spot B) control the LED brightness differently according to the movement of the sun, because office1 and office 2 are more affected by sunlight than the hallway and parking lot. In addition, as shown in Fig. 6, 7, comparing office1 and office2, the LSL light (LSL a1, a2 and LSL b1, b2) is controlled differently, depending on the time and LSL location, because of the different degree of entering daylight influence factor. If the event occurs in office at lunch time (in Fig. 6, LSL control at 12pm ∼ 1pm in the office), it is controlled by using the formula below for when the users are not in the office.

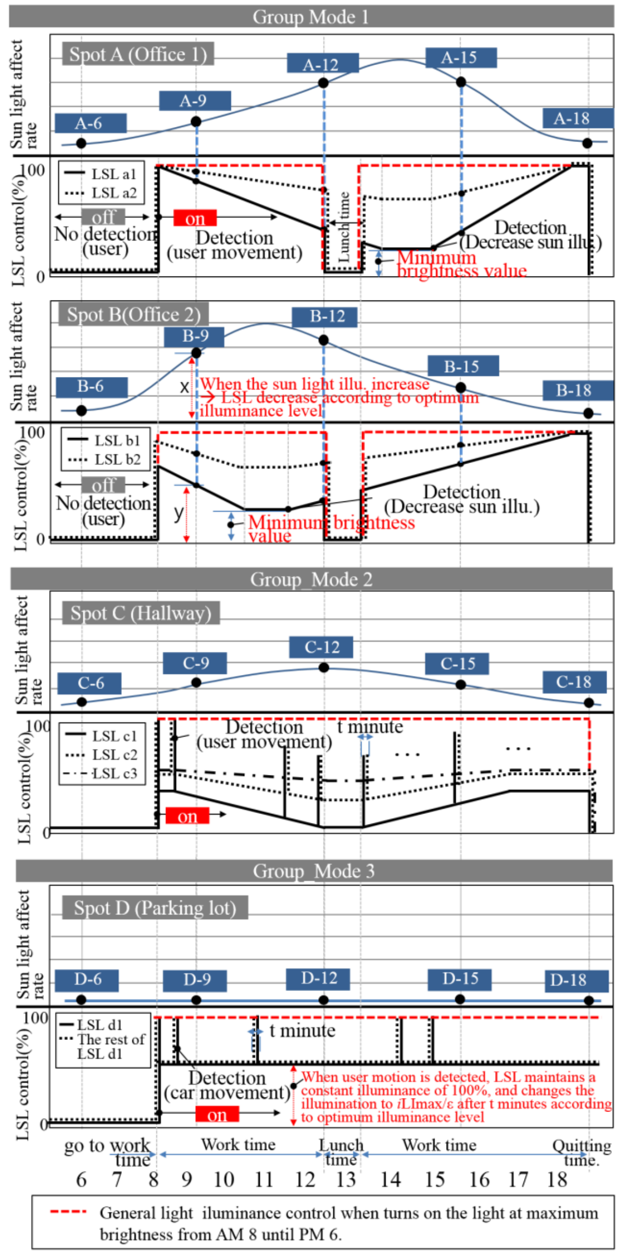

Fig. 6 Sunlight affects rate and energy efficiency of LSL illuminance control of each room

$$iLIe = iLIp/2 \tag{4}$$

Group_Mode 2: In the hallway, if the user movement

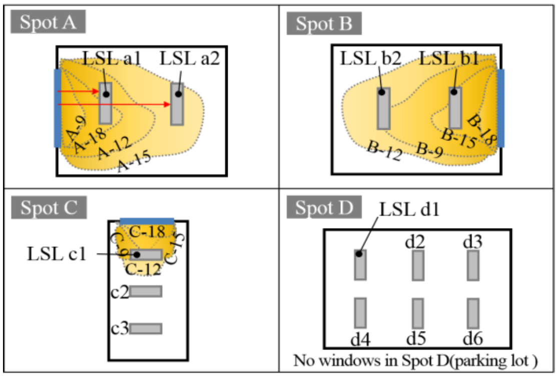

Fig. 7 Sunlight affect diagram (refer to Fig. 6 and Table 2)

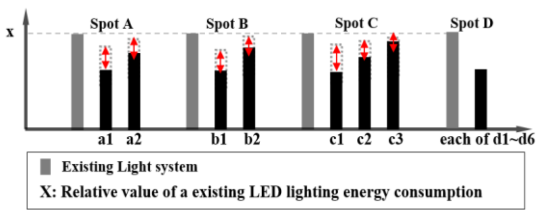

Fig. 8 Predictive value of energy saving

is detected, after t minutes the LSL illuminance is controled through formula (3), because the hallway is a place that is less affected by sunlight. In Fig. 6, unlike the parking lot, the LSL light in the hallway changes illuminance at 9am ~ 5pm because the hallway is affected by the sun, but the parking lot is not. In Fig. 7 in spot C LSL c3 is less affected than LSL c1, c2. So LSL c3 control graph is similar to the mode 3 graph.

Group_Mode 3: Exceptionally, the parking lot is not affected by the daylight influence factor. As in Fig. 6, in the parking lot, when the LSL detects a vehicle movement, it turns on; and after a certain period of time (t minute), reduces to iLImax/ε intensity per formula (1).

5. Discussion

In Fig. 6, the red line is a graph that shows the general light illuminance control when it turns on the light at maximum brightness from 8 AM until 6 PM and during normal weather conditions. But as in Fig. 8, if the LSLs are operated during rainy days, after work hours, or any other events, the energy saving rate decreases lower than the proposed scenario in Fig. 6. The focus of our letter is to show that it is possible to effectively control a building's LED lighting through the energy modeling and energy awareness group control.

6. Conclusion and Future Work

This paper shows a building LED light system that operates through energy analysis and user movement analysis. The results of this study show that our proposed system controls the LED light illuminance according to the sun's movement, user movement, weather, and environmental factors. Furthermore, it will prevent the wastage of energy, and improve user satisfaction. We believe that the building LED light control through energy analysis and user pattern analysis can be used to reinforce government-mandated energy-saving policies. If we apply to not only building light control, but also HVAC equipment control and power control in buildings with Smart Grid and Building Energy Management System (BEMS), it will provide more effective methods for energy efficiency in buildings.

Acknowledgments

This research was supported by the MSIP (Ministry of Science, ICT and Future Planning), Korea, under the ITRC (Information Technology Research Center) support program (IITP-2015-H8501-15-1018) supervised by the IITP (Institute for Information & Communications Technology Promotion), and by the Human Resources Development program (No. 20154030200860) of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korea government Ministry of Trade, Industry and Energy.

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