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Applications of Control Algorithms for Dimming Operations of Electric Lighting Fixtures in a Small Office

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Abstract : This study examines the influence of system components of photoelectric dimming control systems on dimming control performance. Field measurements were performed and a series of computation were conducted. Continuous and integral reset control algorithms were used in connection with two photosensor shielding conditions. Results indicate that the change patterns of daylight illuminance of unshielded photosensor were similar to those of desktop illuminance. When continuous dimming control algorithm was used, unshielded photosensor conditions failed to meet a target illuminance. For the partially-shielded photosensor conditions, lighting fixtures overshot the desktop and less energy savings was achieved compared to the condition of unshielded photosensor. When the integral reset dimming control was used, the system failed to keep enough task illuminance. The desktop illuminance by electric light showed sudden peak values with no dimmed light for a particular time period. Partial shielding conditions were successful under overcast sky conditions, but no lighting energy savings was achieved. Desktop illuminance and light output correlated strongly. The ANOVA test results for the correlation were effective under a significance level of 0.01.

Key words : System components, Photoelectric dimming control, Photosensor, Control algorithm, Sky, Integral reset, Target illuminance, Lighting energy

1. Introduction

Visual environment in a space of buildings is generally maintained by a variety of light sources that provide enough luminous flux for an effective target illuminance. In lighting design procedures, lighting fixtures are selected and positioned at appropriate positions in space in order to provide the necessary illuminance levels. A good way of lighting design is to meet the illuminance on workplanes using electric light to prevent potential complaints from occupants.

When the illuminance is met only by electric light, lighting fixtures consume electricity. It is known that lighting energy consumption is a large portion of whole energy consumed in buildings (U.S. Department of Energy). In order to save electric lighting energy and improve visual environment, a variety of methods using daylight have been suggested (Kim, & Mictrick 2001; Mistrick, Chen & Bierman 2000; Reinhart & Walkenhorst 2001; Vine, Lee, Clear, DiBartolomer & Selkowitz 1998).

Photoelectric dimming control systems generally achieved reasonable control performances under limited daylight and sky conditions when daylight was available enough in space (Mistrick & Thongtipaya 2002; Mistrick & Casey 2011; Kim & Kim 2007; Kim & Song 2007).

Since the electric lighting fixtures were operated during daytime and nighttime on a daily basis in buildings, a strategy for lighting energy savings using daylight needs to be discussed. In particular, the utilization of daylight under diverse sky conditions and components of photoelectric control systems need to

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be studied for appropriate applications of dimming controls.

Therefore, this study examines the control performance of photoelectric dimming systems under various daylight conditions to verify how the dimming system functions according to system components of photoelectric dimming control systems. Field experiments were performed in summer to monitor the variation of daylight under sky conditions. Based on the monitored data, control performances of photoelectric dimming systems were predicted.

2. Research Method

2.1. Field measurement conditions

Field measurements were conducted in a full-scale mock-up space to collect daylight illuminance levels that vary according to the positions of sun and sky conditions. The space was located in Ann Arbor, USA (Latitude: 42°14'N, Longitude: 83° 32').

Figure 1 shows the layout of space. The space was 3 m wide, 4.2 m deep and 2.81 m high. Window was installed on the south-facing facade of space. The dimension of window was 1.42 m wide and 2.03m high. The window was covered with clear glazing and the transmittance of glazing for light was 79 %.

The space was furnished like an actual small private office space. Venetian blinds were installed on the window to control the incoming daylight. The depth of each blind slat was 2.54 cm and distance between each slat was also 2.54 cm. The tilt angle of each blind slat from horizontal plane was zero degree.

The wall surfaces were finished with wall paper with light beige color. The floor was covered with brown wood. A desk with a dimension of 1.5 m by 0.75 m by 0.75 m was installed in the center of space.

An array of 0.6 m by 0.6 m suspended girds was installed on the ceiling to place lighting fixtures. Four recessed fluorescent lighting fixtures were installed on the ceiling and the rest of ceiling area was covered with white acoustic panel boards. The layout out of lighting fixture is shown in Figure 1.

Detailed configurations of the lighting fixture is shown in Figure 2. The fixture type was a recessed 0.6 m by 0.6 m parabolic fluorescent troffer with 7.5 cm louvers. Three by three arrays of cells were applied to the fixture. Two T8 U-shaped fluorescent lamps were installed and each lamp consumed 32 W. The color temperature of lamp was 5000K. The fluorescent lighting fixtures with full light output provided 700 lx, which is required for office tasks.

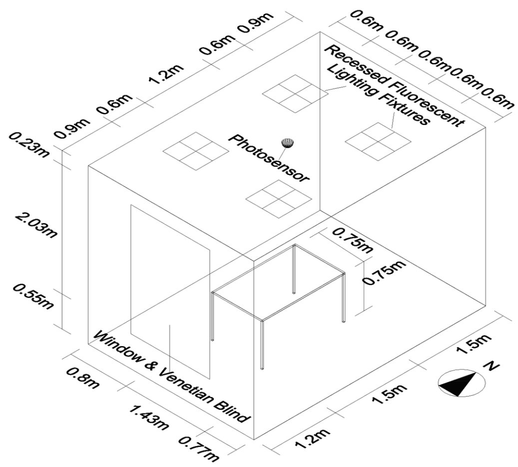

Figure 1. Layout of full-scale mock-up space.

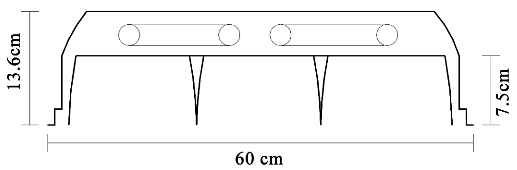

Figure 2. Section of lighting fixture.

2.2. Data monitoring

The variation of daylight illuminance was monitored using multiple photometirc sensors manufactured by "L" company. The sensors detects signals in current and coverts into illuminance based on calibration constants assigned to them. The sensitivity of sensor is 20 mA/100klx (LI-COR).

An automatic data logging system manufactured by “C” company was used for automatic data recordings during given intervals. The logging system detects signals in voltage. Since the photometric sensor detects signals in current and the data logging system detects signals in voltage, a resistance was placed

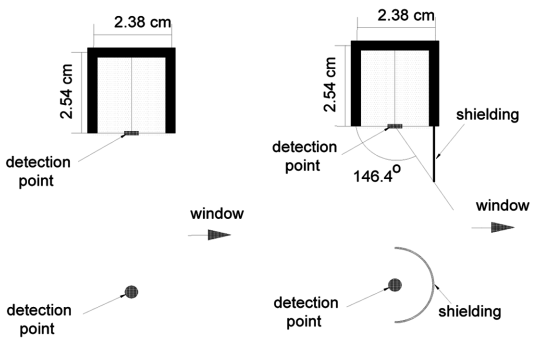

Figure 3. Configurations of potometric sensors (Left: unshielded, Right: partially-shielded).

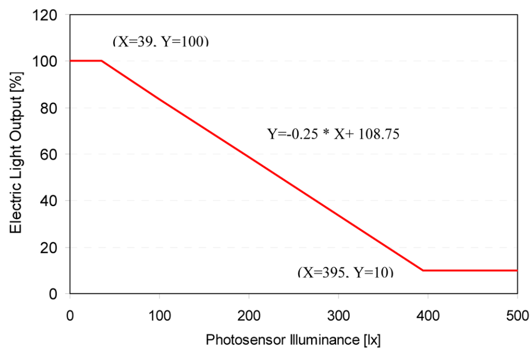

Figure 4. Continuous dimming control algorithm.

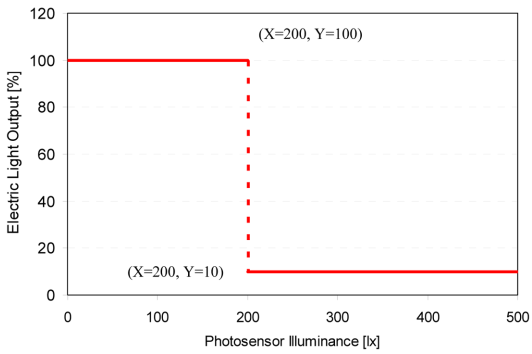

Figure 5. Integral reset control algorithm.

between the photometric sensor and data logging system.

Outdoor horizontal and vertical illuminance levels were monitored. Desktop illuminance levels were measured at five points along the center line of space. The illuminance levels on wall surfaces were also measured. In order to examine the variation of daylight illuminance, two photometric sensors were placed at the center of ceiling.

Two shielding conditions, such as unshielding and partial shielding, were applied to the photometric sensors. Detailed configurations of the shielding conditions are described in Figure 3. The shielding conditions controlled incoming daylight flux to the detection point of photometric sensor.

Data monitoring was performed on a daily basis from April to August. Monitoring interval was 1 minute and 5 minutes according to monitoring conditions. During the monitoring period, the blind slat of Venetian blind was horizontal to floor, and electric lighting fixtures were not operated. The monitored daylight illuminance was used for the computation of final electric light output that affects desktop illuminance levels. The data monitored in July and August were used in this study.

In order to examine the influence of control algorithms on electric light output, two different control algorithms were used. One was a continuous dimming control algorithm and the other was an integral reset control algorithm. Detailed variation of electric light output according to the control algorithms is shown in Figure 4 and 5.

The continuous algorithm generates 100% and 10% of electric light output when the photosensor signal was less than 39 lx and greater than 395 lx, respectively. Between the two levels, light output was controlled linearly. The integral reset algorithm generates 100% of electric light output until the photosensor illuminance becomes 200 lx. Beyond the point, the light output becomes 10%. Based on the daylight illuminance on photosensor and the light output by control algorithms, dimming levels for each lighting fixtures were computed.

3. Results

3.1. Variation of daylight illuminance

In this study, daylight illuminance levels were measured to examine the influence of daylight on dimming control performance. Among all data monitored during field measurement periods, data for three rep-

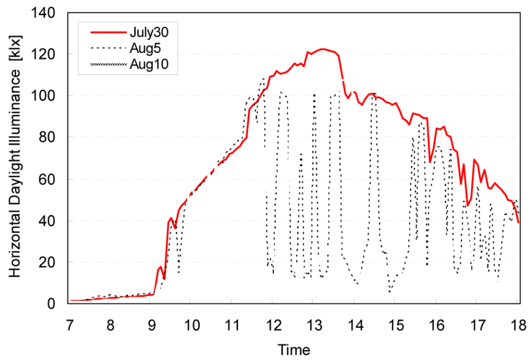

Figure 6. Outdoor horizontal daylight illuminance.

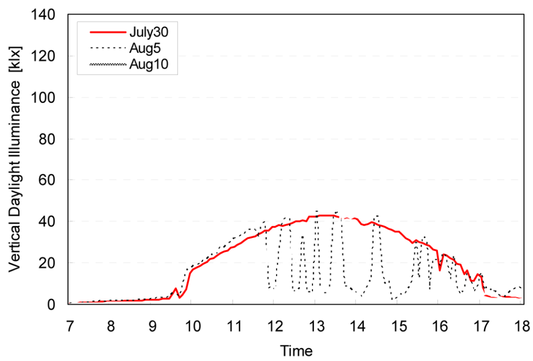

Figure 7. Vertical daylight illuminance to window.

resentative days are selected and discussed in this section.

The variation of outdoor horizontal daylight illuminance and vertical illuminance to window are shown in Figure 6 and 7. Overall, the variation of daylight illuminance was stable during July 30, which appears to be a clear sky condition. No significant fluctuation of illuminance occurred during a whole day. The maximum daylight illuminance was 122.5 klx.

Under the partly cloudy sky conditions on August 5, the illuminance varied showing significant fluctuation ranges. The illuminance was unstable and the maximum illuminance was 108.2 klx. The illuminance on August 10 represents that the sky conditions was partly cloudy and overcast. In particular, from 14:00 to 18:00 the sky condition was overcast, where daylight illuminance changed showing relatively stable variation ranges. During the period, the maximum illuminance was 33.22 klx.

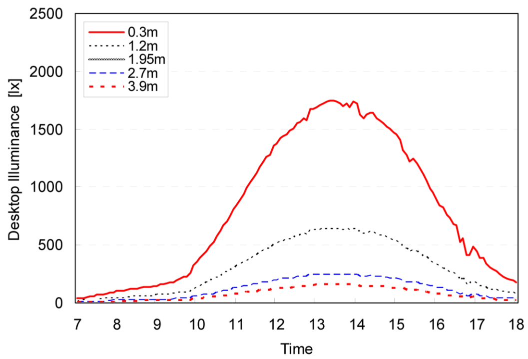

Figure 8. Daylight illuminance on desktop (July/30).

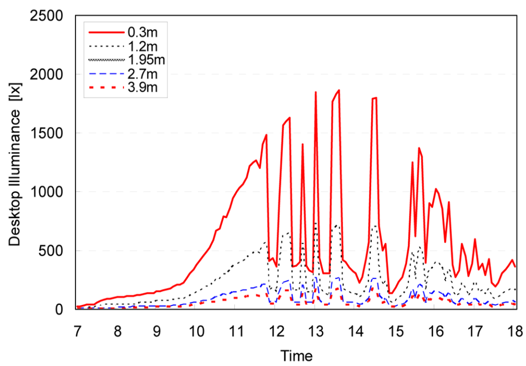

Figure 9. Daylight illuminance on desktop (Aug/5).

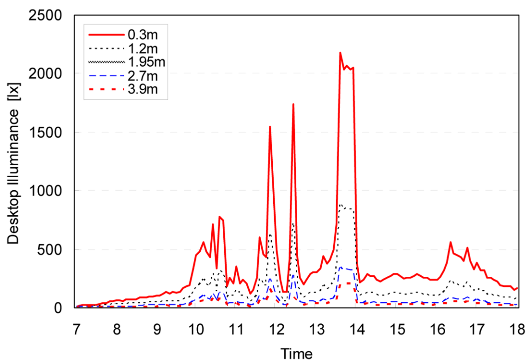

Figure 10. Daylight illuminance on desktop (Aug/10).

The vertical illuminance to window surface showed similar variation patters to those of horizontal illuminance. The maximum illuminance on a clear sky day was 43.09 klx. For the overcast sky conditions, the maximum illuminance was 9.43 klx.

The daylight illuminance levels on desktop surface are shown in Figure 8 ~10. Overall, the illuminance varied with a very stable pattern during a clear sky day. No significant fluctuation happened for entire monitoring periods. The illuminance at 0.3 m away from window showed greater values compared to other illuminance at different positions. At the center point of desktop, which was 1.95 m from window, the maximum illuminance was 381 lx,

For the partly cloudy conditions, the illuminance levels showed very unstable changes. In particular, the illuminance at 0.3 m away from the window showed significant fluctuation ranges. For the overcast sky conditions on August 10, daylight illuminance on desktop was lower than 154 lx. The change of illuminance levels according to time was very stable.

3.2. Control system performance

The illuminance levels of photometric sensor installed at the center of ceiling were monitored. The variations of photosensor illuminance are shown in Figure 11 ~ Figure 13. Overall, the change patterns of illuminance for unshielded photosensor were similar to those of desktop illuminance under three sky conditions. Due to the shielding conditions around the sensing point, the variations of photosensor illuminance level differ from those of unshielded conditions.

Under clear sky conditions, the maximum illuminance detected by the unshielded photosensor was 384 lx. The change pattern of illuminance detected by the unshielded photosensor was stable. Hence, the electric light output of lighting fixtures controlled by the dimming system appears to generate light output within a stable fluctuating range. The partial shielding allowed the daylight illuminance to change within more stable ranges compared to the unshielding.

For the partly cloudy sky conditions, the daylight illuminance on the unshielded photosensor was unstable showing the maximum fluctuation range of 282 lx. This implies that the light output from fixtures changed within a short time period. Compared to the unshielded conditions, the partial shielding conditions did not generate significant fluctuation ranges of illuminances. Partial shielding conditions detected less

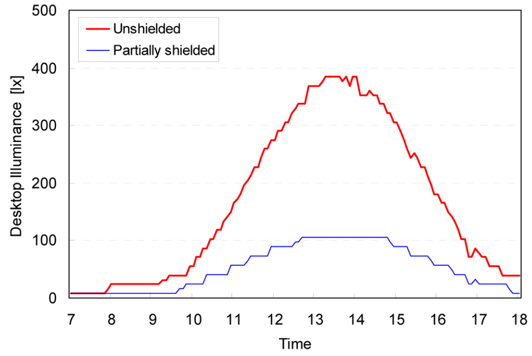

Figure 11. Photosensor illuminance by daylight (July/30).

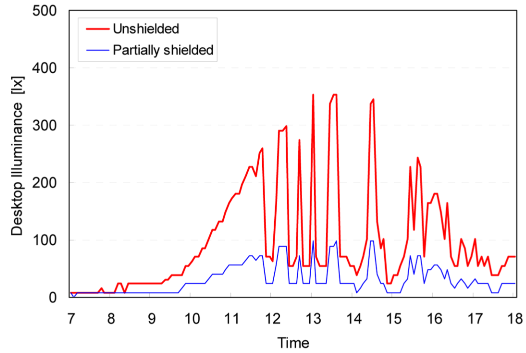

Figure 12. Photosensor illuminance by daylight (Aug/5).

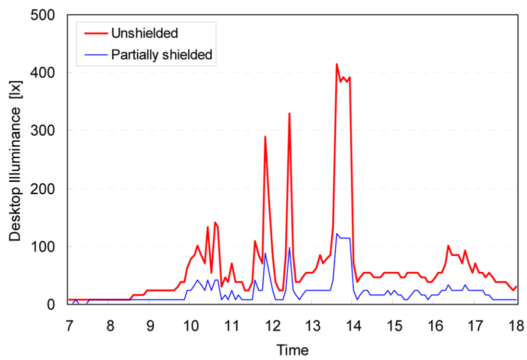

Figure 13. Photosensor illuminance by daylight (Aug/10).

daylight illuminance due to the blocking effect of shielding configurations.

Under the overcast sky conditions in the afternoon on August 10, the daylight illuminance levels detected by the unshielded and partially-shielded photosensor were relatively lower than those under clear and partly cloudy sky conditions. Also, the variation pattern was stable within the monitoring intervals. This may cause stable controls of electric lighting fixtures.

Figure 14 and 15 show selected examples of control system performances achieved by the continuous dimming control system. Overall, the illuminance by electric lighting fixture decreased as daylight illuminance on the desktop increased.

For the clear sky condition, the daylight illuminance increased gradually and lighting fixtures were dimmed according to the continuous dimming control algorithm. Target illuminance of 700 lx was not provided by the dimming control system, although lighting energy appeared to be saved to some degrees. This result occurred since less lighting output was generated by the system due to excessive incoming daylight to the photosensor.

For the partially-shielded photosensor conditions under partly cloudy sky, the target illuminance of 700 lx was met during the majority of time period in a day. As daylight reaches the photosensor, the lighting fixture was dimmed less due to the shielding conditions and meet the required illuminance. However, the lighting fixtures overshot the desktop and less energy savings was achieved compared to the case of unshielded photosensor conditions. The results of this study generally consist with other previous studies (Kim, & Kim 2007; Kim, & Mictrick 2001; Mistrick, Chen & Bierman 2000).

Figure 16 and 17 show selected examples of control system performances achieved by the integral reset dimming control system. For the unshielded photosensr conditions under clear sky, the desktop illuminance by electric light showed sudden peak val-

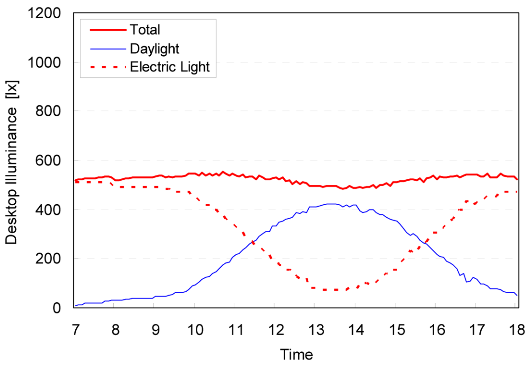

Figure 14. System performance (Continuous dimming control, No shielding, July/30).

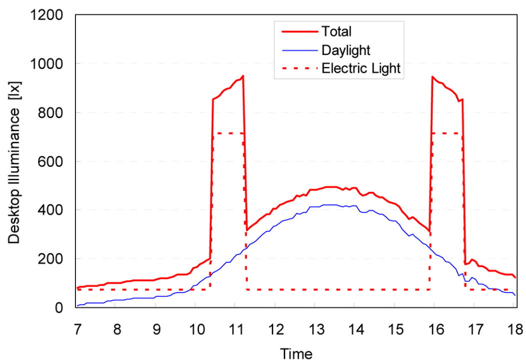

Figure 16. System performance (Integral reset dimming control, No shielding, July/30).

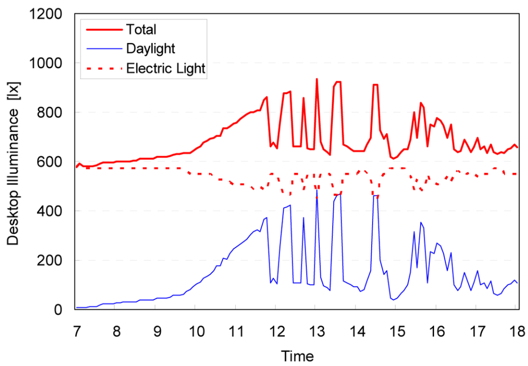

Figure 15. System performance (Continuous dimming control, Partial shielding, Aug/5).

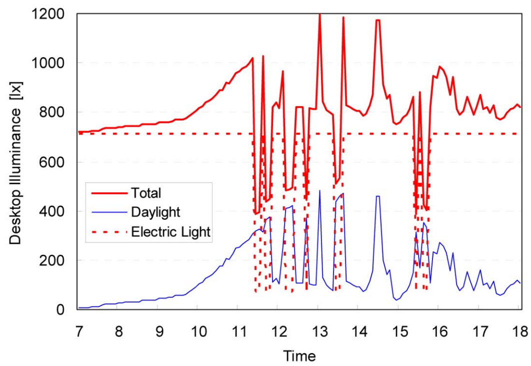

Figure 17. System performance (Integral reset dimming control, Partial shielding, Aug/5).

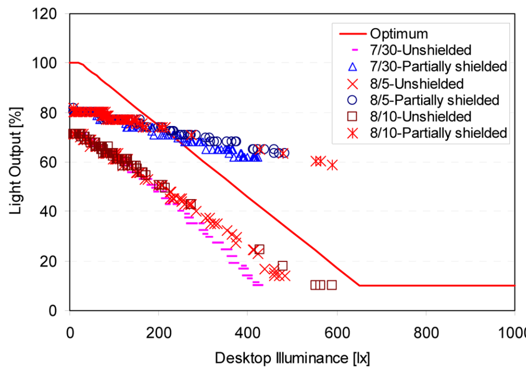

Figure 18. System performance (Continuous dimming control).

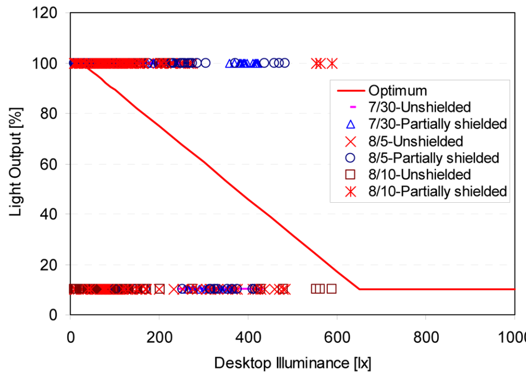

Figure 19. System performance (Integral reset dimming control).

ues with no dimmed light output during a particular time period. For the majority of time periods when daylight was effectively available in space, the maximum dimming occurred and insufficient light was provided to the desktop. Eventually, the integral reset system failed to keep enough task illuminance.

For the partially-shielded conditions under partly cloudy sky, the dimming control system was not fully successful to provide target illuminance. Generally, the partial shielding condition blocks incoming daylight to photosensors and contributes to provide necessary illuminance, when a continuous dimming control system is used.

However, the partial shielding conditions failed to keep target illuminance during certain time periods, when they were used with the integral reset control. It appears that this result occurred, since the integral reset generates 10 % or 100 % of electrical light output according to the photosensor illuminance. When the maximum electric light output was used, excessive desktop illuminance was achieved. On the contrar, the light undershot target illuminance when the minimum electric light output was generated based on the control algorithm. The results of this study generally consist with other previous studies (Mistrick, Chen, Bierman & Flets 2000; Rubinstein, Ward, & Verdeber 1989).

Detailed dimming levels controlled by the continuous and integral reset control are shown in Figure 18 and 19. Frequency analysis for the illuminance levels controlled by the control algorithms is shown in Table 1 ~ Table 4.

The continuous dimming control system combined with the partial shielding conditions successfully kept the required target illuminance during the majority of time periods. Unshielding conditions failed to achieve appropriate illuminance for tasks.

The integral reset control associated with unshielded photosensor conditions failed to keep the task illuminance, since lighting fixtures dimmed excessively. The combination of partial shielding with the integral rest was successful under overcast sky conditions, where daylight was not enough in space. However, no lighting energy savings was

Table 1. Frequency Analysis for Desktop Illuminance (Continuous Dimming Control, Unshielding)

Illuminance Range [lx]	July/30 [%]	Aug/5 [%]	Aug/10 [%]
above 700	0.00	0.00	0.00
650-700	0.00	0.00	0.75
600-650	0.00	0.00	4.51
550-600	0.75	44.36	21.05
500-550	81.20	55.64	73.68
450-500	18.05	0.00	0.00
400-450	0.00	0.00	0.00
below 400	0.00	0.00	0.00
Sum	100.00	100.00	100.00

Table 2. Frequency Analysis for Desktop Illuminance (Continuous Dimming Control, Partial Shielding)

Illuminance Range [lx]	July/30 [%]	Aug/5 [%]	Aug/10 [%]
above 700	51.88	28.57	9.77
650-700	11.28	26.32	19.55
600-650	28.57	34.59	54.89
550-600	8.27	10.53	15.79
500-550	0.00	0.00	0.00
450-500	0.00	0.00	0.00
400-450	0.00	0.00	0.00
below 400	0.00	0.00	0.00
Sum	100.00	100.00	100.00

Table 3. Frequency Analysis for Desktop Illuminance (Integral Reset Dimming Control, Unshielding)

Illuminance Range [lx]	July/30 [%]	Aug/5 [%]	Aug/10 [%]
above 700	15.04	18.80	6.77
650-700	0.00	0.00	0.75
600-650	0.00	0.00	3.01
550-600	0.00	0.75	0.75
500-550	0.00	3.76	0.75
450-500	20.30	2.26	0.00
400-450	9.02	3.76	0.00
below 400	55.64	70.68	87.97
Sum	100.00	100.00	100.00

Table 4. Frequency Analysis for Desktop Illuminance (Integral Reset Dimming Control, Partial Shielding)

Illuminance Range [lx]	July/30 [%]	Aug/5 [%]	Aug/10 [%]
above 700	81.95	90.23	99.25
650-700	0.00	0.00	0.00
600-650	0.00	0.00	0.00
550-600	0.00	0.00	0.00
500-550	0.00	1.50	0.75
450-500	0.00	2.26	0.00
400-450	7.52	3.76	0.00
below 400	10.53	2.26	0.00
Sum	100.00	100.00	100.00

achieved due to the control algorithm.

3.3. Correlation analysis

A linear regression method was employed in this study to examine the effect of daylight illuminance to dimming control systems. For the analysis, desktop illuminance by daylight was used as an independent variable and electric light output was used as a dependent variable. The dependent variable contains light output generated by the continuous and integral reset control algorithm.

Figure 20 shows the linear relationship between the desktop illuminance by daylight and electric light output controlled by the dimming systems. Overall, the light output was decreased as the desktop illuminance by daylight increased.

The slope of regression line for the unshielded photosensor conditions was steeper than that of partially-shielded conditions. It implies that dimming levels controlled by unshielded photosensor conditions is greater than those by the partially-shielded conditions.

The desktop illuminance and light output correlated strongly. The coefficient of determination (r^2) was 0.954 ad 0.9636 for partially-shielded and unshielded photosensor conditions. This result implies that the error variance can be reduced by 95.4 % and 96.36 %, when desktop illuminance was used to predict electric light output controlled by the partially-shielded and unshielded photosensor,

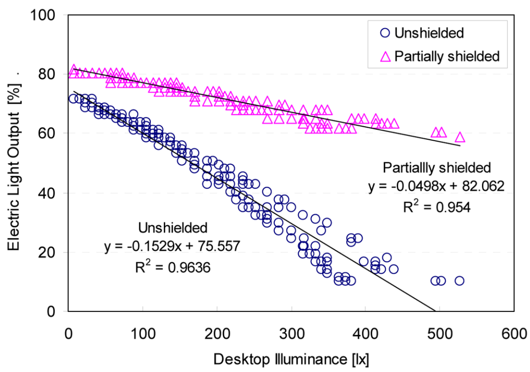

Figure 20. Correlation between desktop illuminance by daylight and electric light output reset control algorithms.

Table 5. ANOVA for Relationship between Desktop Illuminance and Electric Light Output by Unshielded Photosensor

Variable	Unstandardized Coefficient		t	Sig.
	B	Std. Error		
(Constant)	75.56	0.271	279.11	0.00
Desktop	-0.153	0.001	-102.6	0.00
ANOVA	F(1, 397) =10530.21 , Sig. = 0.00, R^2 = 0.964			

Table 6. ANOVA for Relationship between Desktop Illuminance and Electric Light Output by Partially-shielded Photosensor

Variable	Unstandardized Coefficient		t	Sig.
	B	Std. Error		
(Constant)	82.01	0.099	825.66	0.00
Desktop	-0.049	0.001	-90.86	0.00
ANOVA	F(1, 397) =8255.69 , Sig. = 0.00, R^2 = 0.954			

respectively. The ANOVA test results summarized in Table 5 and 6 imply that the linear analysis result was effective under a significance level of 0.01.

4. Conclusions

Field measurements and a series of computations were conducted in this study to examine the influence of system components of photoelectric dimming control systems on dimming system performances. Two control algorithms were combined with two photosensor shielding conditions. A summary of findings is as follows.

1. The change patterns of illuminance for unshielded photosensors were similar to those of desktop illuminance under sky conditions. Under clear and overcast sky conditions, the change pattern of unshielded photosensor illuminance was stable within monitoring intervals.

2. When a continuous dimming control algorithm was used, unshielded photosensor conditions failed to meet target illuminance. This result occurred since less lighting output was generated by the system due to excessive incoming daylight to the photosensor. For partially-shielded photosensor conditions, the lighting fixtures overshot the desktop and less energy savings was achieved compared to the case of unshielded photosensor conditions.

3. When an integral reset dimming control was used, dimming control systems failed to keep enough task illuminance on the desktop. The desktop illuminance by electric light showed sudden peak values with no dimmed light output during a particular time period. For the majority of time period when daylight was effectively available in space, the maximum dimming occurred and insufficient light was provided to the desktop. This result occurred since the integral reset control generates 10 % or 100 % of light output according to the photosensor illuminance. The combination of partial shielding with the integral reset control was successful to provide a task illuminance under overcast sky condition, but no lighting energy savings was achieved.

4. A strong linear correlation existed between the desktop illuminance and light output controlled by the dimming systems. The coefficient of determination (r^2) was 0.954 ad 0.9636 for partially-shielded and unshielded photosensor conditions. This result implies that the error variance can be reduced by 95.4% and 96.36%, when desktop illuminance was used to predict electric light output controlled by the partially-shielded and unshielded photosensor, respectively. The ANOVA test results for the regressions imply that the linear analysis results were effective under a significance level of 0.01.

In this study, field measurements and a series computations were performed under a limited daylight conditions to examine the influence of daylight on dimming controls. The result of this study confined to theoretical computations based on the daylight illuminance on photosensors, which is a starting point of dimming control system. Comparing the analysis results of dimming performance with actual field measurement data under diverse weather conditions would be helpful.

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