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Dynamic illuminance measurement and control used for smart lighting with LED

Yingming Gao [a], Yukai Cheng [a], Huanyue Zhang [b], Nianyu Zou [a,*]

[a] Research Institute of Photonics, Dalian Polytechnic University, Dalian 116034, Liaoning, China
[b] School of Materials Science and Engineering, Dalian University of Technology, Dalian 116024, Liaoning, China

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ABSTRACT

The indoor energy management of lighting is essential for the construction of a smart city; a lighting system that dims electric lights based on the daylight level helps in energy conservation. One of the most common methods to achieve such daylight control is to measure the combination of daylight and electric light, and to determine the dimming level of the electric light. Based on the PWM dimming principle, we present a low computation cost and partial-feedback closed loop control scheme for LEDs, which only measures and feedbacks the contribution of daylight, not that of both light levels, to determine the output of the electric light. Using the photo sensor TEMT6000, a prototype is presented to verify the partial feedback scheme. Experiments show that the partial feedback controller has the capability to stabilize illuminance satisfactorily.

1. Introduction

Smart cities are responsible for balancing environmental and natural resources; hence, energy-efficient lighting is paramount not only to reduce energy costs but also to promote environmental and economic sustainability [1]. Considering that 30–45% of the electrical energy consumed by buildings is used for lighting [2], besides urban lighting, the energy management of indoor lighting should be an important issue to build a smart city; the potential of energy conservation for indoor lighting is great, as much as 60% in some areas [3,4]. Daylight harvesting is efficient to save the indoor lighting energy consumed by buildings, with the help of automatic control technology. To balance energy consumption and the comfort of occupants, daylight harvesting dim electric light is used to keep mixed illuminance constant on a workplane, when daylight is insufficient [5–7].

The actual illuminance of a workplane is given by the combination of both lighting with daylight and electric. As we know, most closed loop control on illuminance is measured with a photodetector and the artificial light is dimmed based on the measurement [8–10]. However, literature [11] presented an open-loop lighting control scheme, with LEDs acting as both the sensor and emitter in turn; the illuminance was measured when the LED worked with the sensing mode, so the daylight was separated from the electric light, hence, only the daylight contribution was used to dim the electric light.

Taking advantage of the ultrafast switching speed of LEDs, we propose a partial closed loop control scheme with a photo sensor, which completes measurements in the off period of the LEDs, and then only part of the illuminance contributed by daylight is measured and returned. Compared with the LED acting as a sensor in [11], the photo sensor is characterized as reliable and mature. Otherwise, no complicated protocol and low computation cost mean partial feedback is easy to be realized.

Originally, LEDs were made as a light emitter not detector, all emphasis is laid on improving and stabilizing the performance of lighting, no matter what design and manufacture. Acting as a light sensor, consistency might not be guaranteed, so the results provided by the LEDs could change drastically, against batch application. In particular, its responsivity is not adaptive to human eyes, so accurate illuminance is difficult to obtain by reversed LED simply, compared with a specialized photo sensor.

2. Principle of partial illuminance feedback

Enlightened by the principle of PWM dimming, we divided one control cycle T into two time slots; electric light-on slot T_{ON} and electric light-off slot T_{OFF}, where $T = T_{ON} + T_{OFF}$. The map between the time slots and illuminance is shown in Fig. 1. Where E_L is the artificial light illuminance, E_D is the daylight illuminance and

* Corresponding author.

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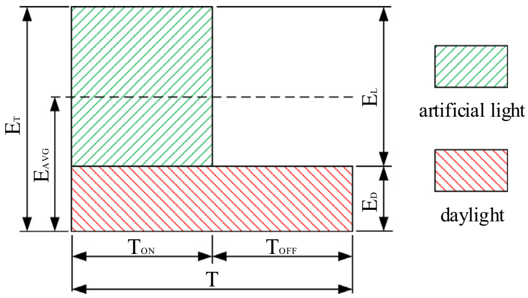


Fig. 1. Map of illuminance and time slots.

$E_T = E_D + E_L$ is the total illuminance, according to the theory of radiosity [12].

According to the principle of PWM dimming, the average illuminance is:

$$E_{AVG} = \frac{(E_D + E_L)T_{ON} + E_D T_{OFF}}{T} \tag{1}$$

Rewriting the above equation to obtain:

$$E_L = \frac{E_{AVG} - E_D}{D_{OVE}} \tag{2}$$

where $D_{OVE} = T_{ON}/T$ is the overall duty-cycle. Based on the above equation, we know that artificial light illuminance E_L could be calculated using D_{OVE} and daylight illuminance E_D alone, not the combination, given the average illuminance E_{AVG}. Obviously, D_{OVE} is configurable in advance and E_D is dynamically measurable. Considering the linear PWM dimming character of LEDs [13], $E_L = E_{L\_MAX} \cdot D_{DIM}$, where E_{L_MAX} is the maximal illuminance produced by the LED, substituting E_L to the left side of Eq. (2) for $E_{L\_MAX} \cdot D_{DIM}$, then the dimming duty-cycle D_{DIM} used in the duration T_{ON} is:

$$D_{DIM} = \frac{E_{AVG} - E_D}{E_{L\_MAX} \cdot D_{OVE}} \tag{3}$$

In Eq. (3), D_{DIM} is proportional to the difference between the average illuminance E_{AVG} and daylight illuminance E_D. The partial feedback and the P controller, a special case of proportion integration differentiation (PID) controller, are similar in expression. However, given the LED and overall duty-cycle D_{OVE}, the proportional coefficient $1/(E_{L\_MAX} \cdot D_{OVE})$ of Eq. (3) could be confirmed in advance, without a parameter tuning process, which is indispensable to a PID controller. Partial feedback directly gives the definition of the proportional coefficient, which is clearer than that by the P controller. Therefore, the partial feedback controller is more adaptable than the P controller; its input is the difference between E_{AVG} and E_D, and the output is the dimming duty-cycle D_{DIM}.

Partial feedback must exclude electric light from the mixed to obtain the contribution of daylight only. We extracted daylight from the combination by switching off the LED completely ahead of measurement, so the contribution of daylight was measured alone before being compared with a given average illuminance E_{AVG}, i.e., the input variable E_R. Then, the difference between E_R and E_D was converted to D_{DIM} using Eq. (3) for the partial feedback controller, and D_{DIM} was input to dim electric light for a reasonable E_L, shown in Fig. 2(a). Compared with Fig. 2(b) showing general feedback, only daylight, not the light combination, is fed back to input. Taking advantage of the ultrafast switching speed of LEDs, the extraction could be fast enough to avoid flicker.

3. Control algorithm of partial feedback

The function of the control algorithm is to dynamically measure daylight illuminance and calculate the dimming duty-cycle based on the principle of partial feedback, and to maintain constant mixed illuminance, in a series of control cycles. To control the illuminance, three operations, i.e., the measurement, calculation, and output of the dimming signal should be performed for every control cycle, composed of T_{ON} and T_{OFF} as mentioned above. The measurements, together with the calculations, were done successively for the duration of T_{OFF}, while the signal was output for the whole T_{ON}, as shown in Fig. 3.

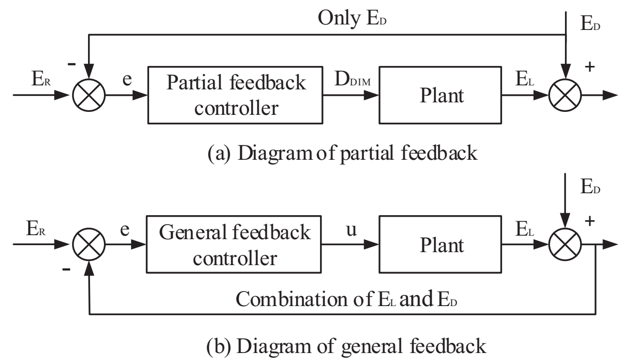


Fig.2. Diagram of partial feedback and general control loop.

According to Eq. (1), the average illuminance of the nth control cycle is:

$$E_{n\_AVG} = \frac{(E_{n\_D} + E_{n\_L})T_{ON} + E_{n\_D} T_{OFF}}{T} \tag{4}$$

where E_{n_D} and E_{n_L} are the separate illuminance contributions of the daylight and electric light of the nth control cycle. For LED $E_{n\_L} = E_{L\_MAX} \cdot D_{n\_DIM}$, where D_{n_DIM} is the duty-cycle of the PWM dimming signal output for the nth T_{ON}, E_{L_MAX} is the maximal illuminance made by the LED. Substituting E_{n_L} with $E_{L\_MAX} \cdot D_{n\_DIM}$ into the above equation, the average illuminance of the nth cycle is presented as follows:

$$E_{n\_AVG} = \frac{(E_{n\_D} + E_{L\_MAX} D_{n\_DIM})T_{ON} + E_{n\_D} T_{OFF}}{T} \tag{5}$$

Substituting the overall duty-cycle $T_{ON}/T = D_{OVE}$, $T_{OFF}/T = 1 - D_{OVE}$ into the above equation, the dimming duty-cycle D_{n_DIM} can be calculated by the following:

$$D_{n\_DIM} = \frac{E_{n\_AVG} - E_{n\_D}}{E_{L\_MAX} \cdot D_{OVE}} \tag{6}$$

The above equation can be used as a digital controller of partial feedback, if E_{n_AVG} is expected to be constant, the basic character of daylight harvesting; the controller could be applied to dim electric light based on daylight alone to stabilize illuminance on the workplane, in a series of control cycles. In addition, illuminance should

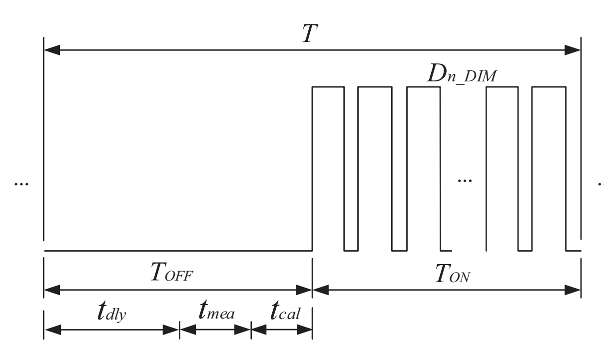


Fig. 3. Definition of one control cycle.

be measured after a time interval t_{dly}, starting from the beginning of T_{OFF} until the LED is discharged completely. Otherwise, the afterglow of the LED makes measurements greater than the actual illuminance made only by daylight, and the combined light lower than the expectation.

Overall, the duty-cycle D_{OVE} concerns allocation of one complete cycle of sampling, calculation, and output, not simply as a parameter of the dimming signal, different from the duty-cycle of a rectangular wave, which is defined as the ratio of high-level time to one cycle. Although D_{OVE} influences the quantity of illuminance, with the same dimming duty-cycle D_{n_DIM}, the bigger D_{OVE} is, the longer the output time T_{ON} is, then, a greater illuminance is obtained, according to Fig. 3.

When the power is off, the LED gradually, not instantly, extinguishes because of the energy saved by the capacitor and inductor of the circuit, besides the fluorescent powder used by the LED, as shown in Fig. 4. Light emitted by the LED in the power-off state is called afterglow. The measured illuminance is the sum of the daylight illuminance E_D and afterglow illuminance E_{L_A}, not to be mistaken for E_{n_D} of Eq. (6), when afterglow exists. Because the sum was greater than E_{n_D}, D_{n_DIM} calculated by Eq. (6) was lower than the expectation, and E_{n_L} output by the artificial light was lower consequently, according to $E_{n\_L} = E_{L\_MAX} \cdot D_{n\_DIM}$. However, the variation of daylight is relatively slow, almost unchangeable over a short period. Then, the lower E_{n_L} makes the combined illuminance less than the expectation. Hence, measurement of the illuminance should begin when the afterglow is gone.

Based on the visual characteristics of a human, the partial feedback of the illuminance directly calculated the quantity of electric light to compensate the illuminance, different from fuzzy logic and the PID controller partly dependent on experience and tentative to get optimal control results [14].

4. Measurement on illuminance

For a general lighting application scenario, measurement time should be short enough to avoid flicker and facilitate the comfort of occupants, however, a resolution of 50 lx, or even less for the illumination measurement, is acceptable. Without calibration, the digital ambient light sensor BH1750FVI outputs the amount of illuminance directly through the I^2C interface, which the system realizes simply compared with the analogue sensor. However, due to its slow clock frequency, typically 320 kHz, measurement time is relatively long, at least 16 ms. With an analogue illuminance sensor and high-speed ADC, the measurement time could be as short as dozens of microseconds or less.

As shown in Fig. 5(a), we present a smart LED lighting driver with STC15F2K60S2 an 8-bit microprogrammed control unit (MCU) integrated with a high-speed 10-bit analog-to-digital converter (ADC) as the processor, TEMT6000 a silicon NPN epitaxial planar phototransistor as the sensor, and PT4115 a constant current buck converter as the driver. The photo-current of TEMT6000, proportional to the intensity of visible light, was converted into voltage by a 10 KΩ resistor connected with its collector in series, then, the voltage was digitized by the ADC of STC15F2K60S2. With a 12 MHz system clock, the conversion time of its ADC is as short as 9 μs. Links among the components of the experiment system are shown in Fig. 6.

The control algorithm mentioned above is applicable to artificial light, with an illuminance almost proportional to the duty-cycle, such as an LED. Driven by the controller, we present this relationship using a 3 W LED from a commercial luminaire, as shown in Fig. 7. According to the measurement, the duty-cycle is nearly proportional to the illuminance and the maximal illuminance E_{L_MAX} was approximately 3100 lx. Obviously, the result is not unique, differing with the location of measurement.

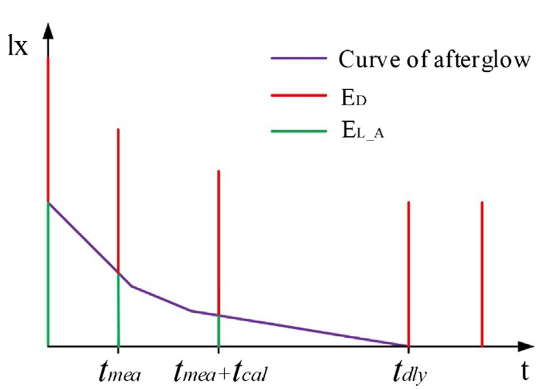


Fig. 4. Effect of afterglow on illuminance.

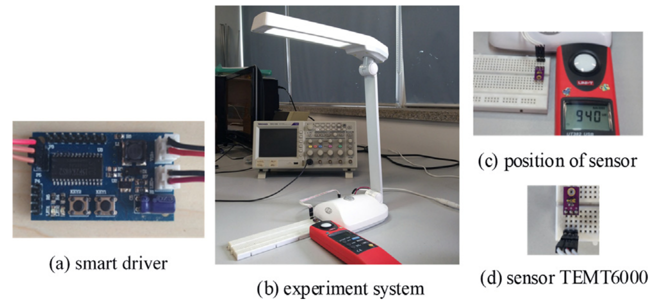


Fig. 5. Images of the experiment system.

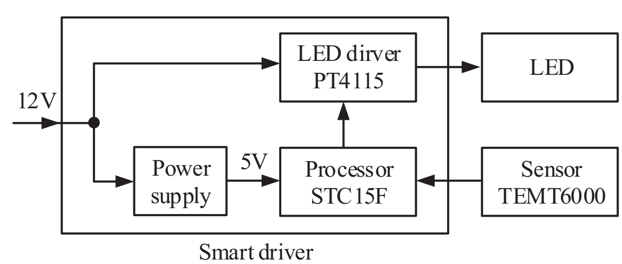


Fig. 6. Block diagram of the system.

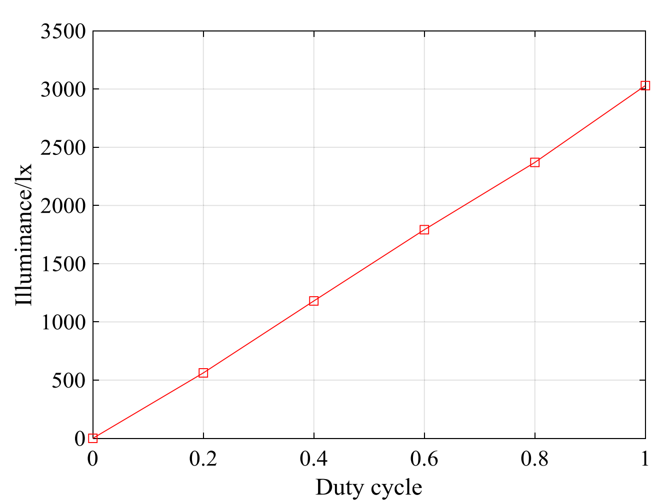


Fig. 7. Relationship between illuminance and duty-cycle.

We present the relationship between the digital value of the voltage and the illuminance. However, the digital value of the voltage converted by the controller fluctuates dramatically with PWM dimming. Besides the short response time of TEMT6000 to light, the conversion time of ADC integrated with STC15F2K60S2 is as short as 9 μs with a 12 MHz system clock, enough to capture the fast fluctuation of the illuminance induced by PWM dimming. To smooth the fluctuation, we used a capacitor above 2 μF connected in parallel with output pin of TEMT6000 module. According to Fig. 8, the resolution of measurement was approximately 5.2 lx, enough for lighting application.

5. Measurement on afterglow characteristics

As mentioned above, the illuminance measurement should not begin until the afterglow of the LED has disappeared completely, when enter time slot T_{OFF}. Otherwise, the illuminance was a combination of daylight and afterglow, greater than pure daylight contribution. Hence, the electric light illuminance E_L was less than the expected, making the combined illuminance insufficient.

We measured the afterglow characteristics of the LED with the experiment system mentioned above. The LED was dimmed by an intermittent PWM dimming signal, output directly through the PWM unit of the MCU, shown in Fig. 9. Illuminance is measured in the gap period of the signal. A soft timer used to set the time delay in advance, was started as soon as the signal entered the gap period. After the preset delay, the measurement start and results were output from the universal asynchronous receiver/transmitter (UART) of the MCU and sent to the upper computer.

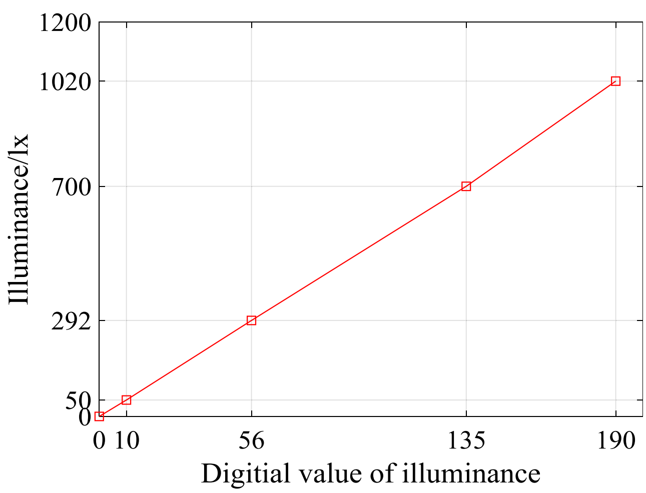


Fig. 8. Relationship between digital value and illuminance.

We used digital values converted by the ADC to represent the illuminance of the afterglow on the tested point. According to Fig. 10, the duty-cycle determined the afterglow property; the bigger the duty-cycle, the higher the initial afterglow was. The afterglow illuminance decreased as the time elapsed and became zero from the initial after 800 μs, when the duty-cycle was 100%. Obviously, the time of an afterglow differs with systems, besides the LED itself, the energy storage character of the capacitor and inductance comprising the driving system both influence the afterglow characteristic.

6. Experiment on illuminance control

With the smart driver presented by this paper, we verify the capability of partial feedback to maintain the expected illuminance, such as 1000 lx on the workplane, when background light is provided by the electric light or daylight. A flow chart to maintain constant illuminance is shown in Fig. 11. Three key parameters, the test resolution, maximal illuminance E_{L_MAX} made by the electric light, and the overall duty-cycle D_{OVE} used in the program are, respectively, 5.2 lx, 3100 lx, and 50%, according to Eq. (6).

6.1. Experiments with artificial light as background

To facilitate adjustment of the background illuminance E_B, an off-the-shelf dimmable LED lamp with a four-level output was used as the provider of background light. The quantity of background illuminance was obtained through adjustment of its position relative to the photosensor and illuminometer, together with the light level of the LED. For example, one obtained series of background illuminance was 0 lx, 38 lx, 214 lx, 522 lx, and 769 lx.

The experiment shows that a partial feedback controller indeed dims electric light properly to compensate for the illuminance when E_B is less than the expected illuminance, E_{EXP}. When E_B is greater than E_{EXP}, the LED was switched off, and illuminance was contributed only by E_B, such as 522 lx and 769 lx, the last two points situated on the blue curve correlated with E_{EXP} 500 lx shown in Fig. 12. The difference between the combined illuminance and

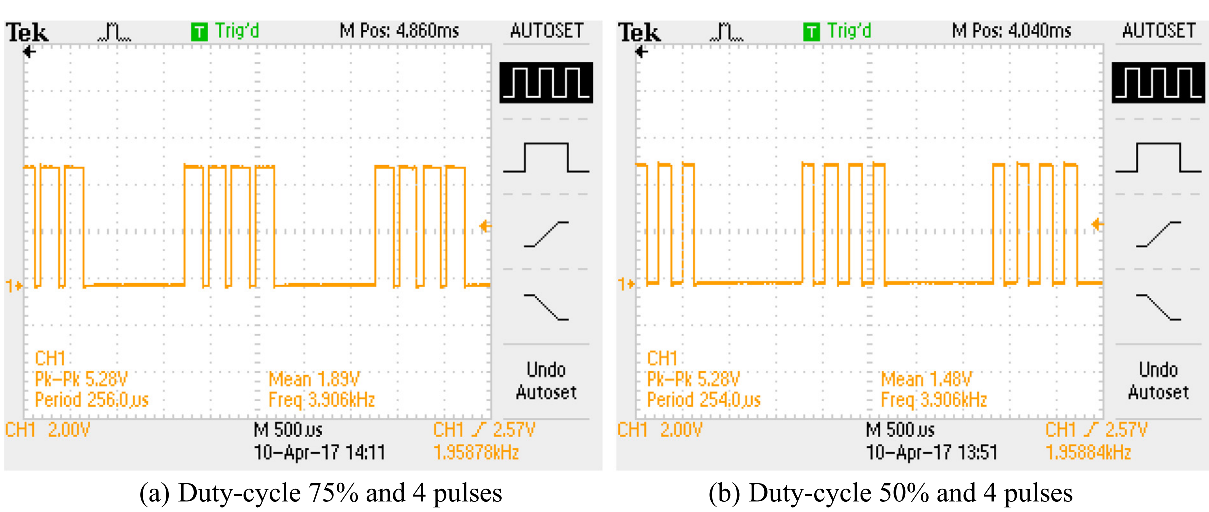


Fig. 9. Dimming signal of LED.

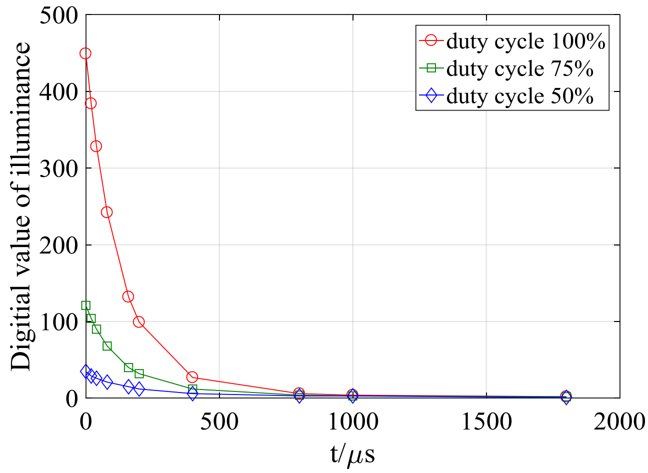


Fig. 10. Afterglow illumination vs. duty-cycle.

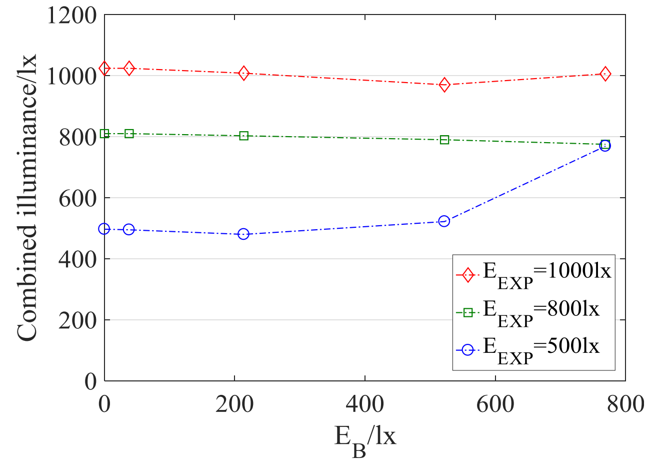


Fig. 12. E_B vs. combined illumination.

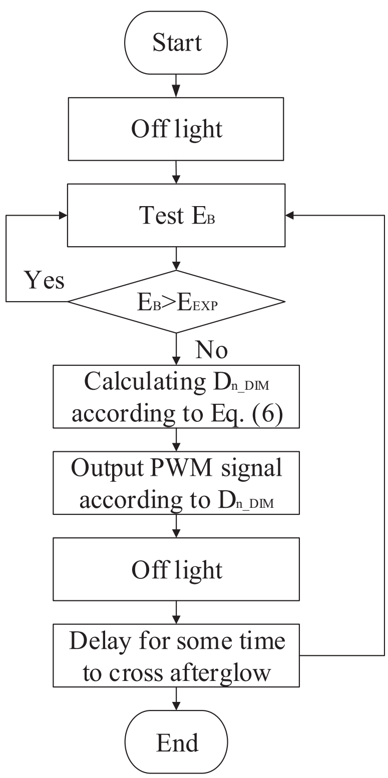


Fig. 11. Flow chart to maintain constant illuminance.

the expected is the maximum of 30 lx. Considering that changes of illuminance less than 50 lx are generally undetectable when indoor lighting ranges from 300 to 1000 lx [15], it is an improvement on the general situation.

6.2. Experiments with sunlight as background

There is a big difference between the combined and expected illuminance E_{EXP} with direct sunlight. At dawn and dusk, when daylight illuminance is less than 50 lx, the difference between E_{EXP} and the actual illuminance is acceptable, but an obvious difference above 400 lx as E_{EXP} = 1000 lx is observed in the morning, when direct daylight is above 2000 lx. The reason should include parameters such as the resolution used in the program was calibrated with vertically incident light, but the photoelectric responsivity of TEMT6000 changes with the incidence angle of light. Direct daylight is hardly vertical to the receiving surface of the sensor; hence, the case conflict with parameters was used. The cosine corrector, specially designed for TEMT6000, should improve the performance of the direct daylight scenario.

Experiments with scattered sunlight were conducted in December, under a home environment close to the north side of a hill. Blocked by the hill, sunlight could not enter the room directly. Two illuminometers with USB interfaces were used, numbered as '1' and '2', respectively. Illuminometer 1 was fixed in the balcony close to the foot of a French window, and was used to record the variation of daylight; illuminometer 2 was placed close to a lamp to test the combined illuminance, with the position relative to the lamp and sensor TEMT6000 the same as that for the calibration process. In Fig. 13, as a reference point, the location of illuminometer 1 is marked as RP, test points, while the locations of illuminometer 2 are marked as TP. Data collected by the illuminometers was uploaded to upper computers automatically through a USB every five minutes, then saved as files by a program.

The experiment was conducted from 6:00 to 18:00 every day, with an expected illuminance of 1000 lx, some experimental results obtained from test point TP, regarding the time vs. illuminance, are presented in Fig. 14. Considering Fig. 11, when the

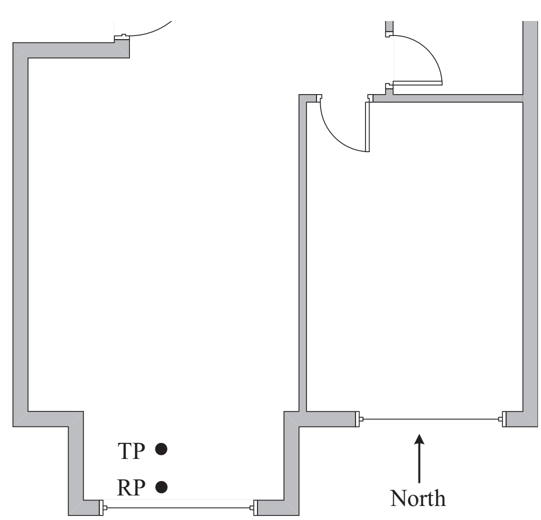
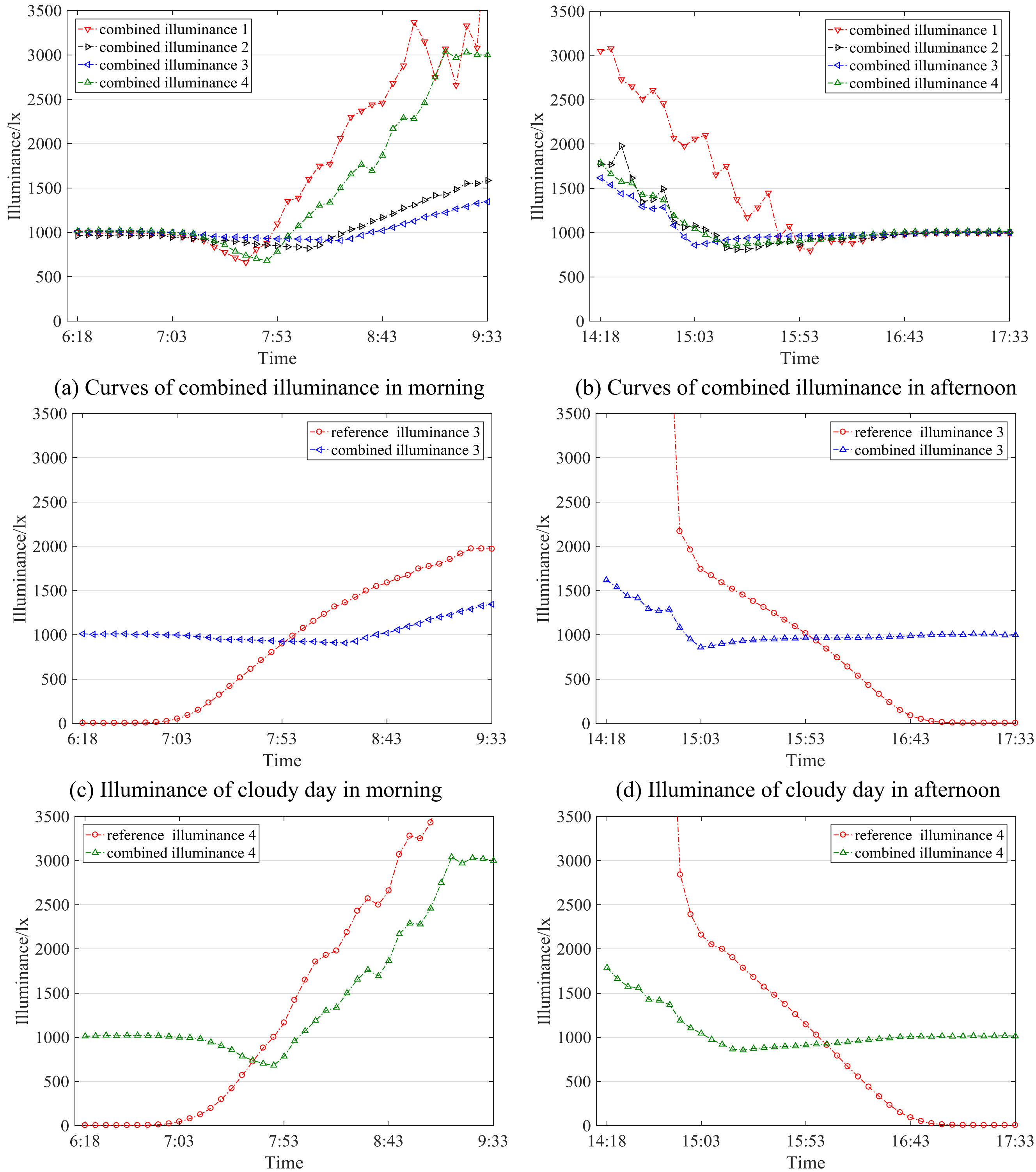


Fig. 13. Location of reference and test points.



(a) Curves of combined illuminance in morning
(b) Curves of combined illuminance in afternoon
(c) Illuminance of cloudy day in morning
(d) Illuminance of cloudy day in afternoon
(e) Illuminance of sunny day in morning
(f) Illuminance of sunny day in afternoon

Fig. 14. Experimental results obtained from points RP and TP.

background illuminance E_B was greater than 1000 lx, the LED was OFF and the partial feedback controller stopped to adjust the illuminance, so parts of the illuminance around 1000 lx are presented, not all. According to the results, the algorithm of partial feedback works well with scattered sunlight, even without cosine correction on sensor TEMT6000.

According to Fig. 14(a) and (b), all combined illuminance curves bend down around the expected 1000 lx, respectively in the morning and the afternoon, with increasing and decreasing daylight. Comparing (c) with (e) and (d) with (f), the amplitude of decline is related to weather conditions, being lower for cloudy than that of sunny. The reason for this might be, besides the block of the hill, clouds scatter the sunlight again, equivalent to the cosine correction performed on TEMT6000, further rectifying the difference with the illuminometer. The variation speed of daylight might reflect the weather situation. In general, the speed on a cloudy day is slower than that on a sunny day; therefore, the cloudy day illuminance given in (c) shows exactly what occurred.

7. Conclusion

Based on the PWM dimming principle, we presented a partial-feedback lighting control scheme for LEDs, which measures illuminance during an OFF light period, with only daylight illuminance used to control the illuminance. Considering the ultrafast switching speed of LEDs and the visual characteristics of humans, the partial feedback controller economically calculates the quantity of electric light to compensate the illuminance; the low computation cost and no parameter tuning make the scheme easy to realize.

The afterglow of LEDs influences the separation of daylight from mixed light. Hence, measurements should be performed when the afterglow has disappeared; otherwise, the results would be higher than the actual, and the mixed illuminance would be lower than expected. We present a smart driver for an LED and test the characteristics of the afterglow. With PWM dimming, the duration of afterglow is mainly determined by the dimming duty-cycle, not pulse number.

Under direct sunlight, illuminance deviation is too big to be acceptable because of the responsive difference between TEMT6000 and the illuminometer. Without cosine correction on TEMT6000, we experimented under artificial light and scattered sunlight, with the results showing that a partial feedback controller could work well. Under scattered sunlight, the combined illuminance deviates from the expected illuminance, such as 1000 lx. When the reference illuminance approaches the expected illuminance, the deviation for a cloudy day is smaller than that for a sunny day.

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