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Adaptive Temperature Control System for LED Array Systems

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Abstract – In this paper, an adaptive temperature control system for plant cultivation is proposed. The proposed method analyzes the internal temperature of red and blue LED arrays and determines the optimal fan speed for various temperature conditions. The adaptive control system is then implemented based on the analyzed data. Hence, the proposed system can better reduce the fan control power and noise than the conventional method. In the experimental results, the error between the simulation model and real system was at most 2.96%. The proposed method reduced the power consumption to 60% that of the conventional system when the target temperature was 38 °C.

Keywords: Light emitting diode, Temperature control, Power reduction

1. Introduction

A light emitting diode (LED) emits light by directly converting electricity into light, and hence, it has more advantages than other types of light sources such as cold cathode fluorescent lamps (CCFLs) and high-intensity discharge (HID) lamps [1]. First, LEDs have better efficiency than other light sources. For example, an HID lamp needs 35 W to produce the same amount of light as LEDs that only consume 21W, which is 60% of the power consumed by an HID lamp [2]. The other advantage of using LEDs is that their brightness can be easily controlled. For example, CCFL must consider the temperature during operation, and hence, the controllable range of the brightness is significantly limited at high temperatures. On the other hand, LEDs can be easily controlled using a high-current rheostat and PWM modulation. Additionally, the wide wavelength of LEDs is one of the reasons that they are now widely used. RGB LEDs can cover the full color spectrum, and therefore are widely used in various applications such as sensory lighting, display devices, and grow light systems for plants, animals, and insects.

However, LEDs radiate a large amount of heat energy when emitting light. When an LED operates, 80% - 88% of the total electricity is converted into heat energy, and this reduces the light efficiency and device stability significantly. Fig. 1 shows the heat transfer problem in an LED system. The heat produced from the LEDs transfers through the fixtures, and this heat can affect the control units, including the microcontroller, when the LEDs operate. Therefore, the heat degrades the performance of the system and causes malfunction, thereby eventually reducing the life of the LED system.

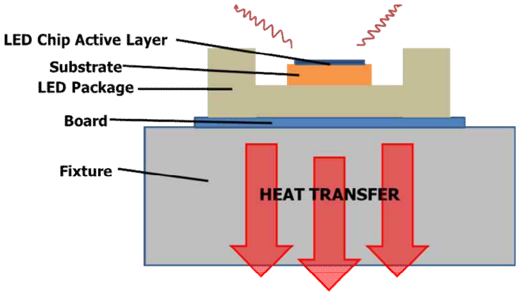

Fig. 1. Heat transfer problem in an LED system

In order to reduce this problem, we propose a novel temperature control system that can adaptively control the temperature of the LED arrays. The proposed system uses multiple cooling fans, and the speed of the cooling fans is adaptively controlled based on the system temperature, thereby enhancing the system stability effectively. To achieve this, the proposed method analyzes the internal temperature of the LED arrays. The data from this analysis is used to determine the optimal fan speed for various temperature conditions. The adaptive control system is implemented using the analyzed data. Hence, the proposed system can optimally decrease the fan noise and control power required with respect to a conventional system using a fan with a fixed speed.

2. Proposed Algorithm

To maintain the optimal temperature of the LED array, the proposed multiple-fan system design considers various physical parameters. The overall block diagram of the proposed system is shown in Fig. 2. First, the LED structure for the target system is determined. Here, various parameters for the target LED system such as LED type, total power, radiant intensity, and forward voltage are extracted. Next, the target system is modelled using the extracted parameters. In the second block, the optimal

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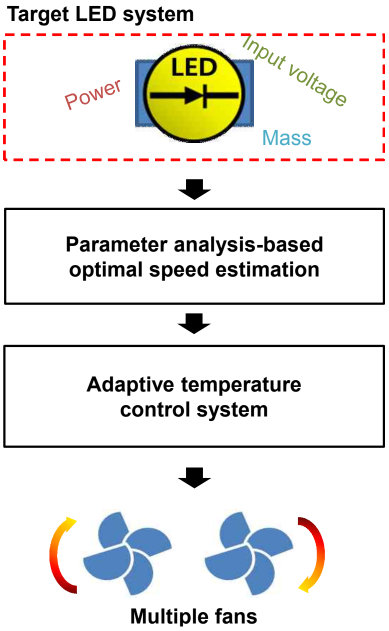


Fig. 2. Overall block diagram

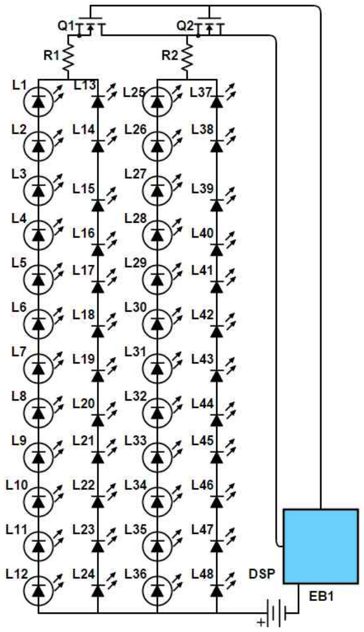


Fig. 3. Equivalent circuit model of the target LED system

speed of multiple fans is calculated based on simulated temperatures output by the optimal model for the target LED system. In this case, the optimal fan speed is computed for different fan speed conditions. After the optimal fan speed is determined, a mapping database is generated. Using this database, the proposed system adaptively controls the fan speed considering different environmental conditions, thereby reducing the internal temperature and noise artifacts.

2.1 Target LED system specification

The target LED system is composed of total 504 units of IWS-L5056-UR-N3 SMD5050 LEDs from ITSWELL [4]. Red and blue LEDs are used in this system, but their brightness and power consumption are different. Table 1 lists the parameters of the red and blue LEDs. The forward voltages of the red and blue LEDs are 2.4 and 3.6 V, respectively, when the forward current is 60 mA. Therefore, the total power consumption of the system is 125 W, and the system can radiate a large amount of heat energy. For example, the radiant intensities of the red and blue LEDs are 22 mW/sr when the forward current is 60 mA. Hence, the heat loss of the red and blue LEDs is 84.7% and 89.8% of the total power, respectively. This could cause severe problems for the physical devices such as unstable operation of the control module or lifetime degradation of the overall system [5].

Table 1. Parameters of the red and blue LEDs

Type	Parameter	Symbol	Conditions	Min.	Typ.	Max.	Unit.
Red	Forward Voltage	V_f	I_F= 60 mA	1.8	-	2.4	V
	Radiant Intensity	I_R		8	-	22	mW/sr
	Peak Wavelength	I_e		650	-	665	nm
Blue	Forward Voltage	V_f	I_F= 60 mA	2.8	3.2	3.6	V
	Radiant Intensity	I_R		8	-	22	mW/sr
	Peak Wavelength	I_e		450	-	475	nm

After determining the target LED arrays, a schematic of an equivalent circuit model (ECM) of the target system is designed to analyze the electrical characteristics. Fig. 3 shows the ECM of the target system. The target system is driven by a DC 12 V input voltage, and the LED arrays are controlled by a pulse width modulation (PWM) method based on metal-oxide semiconductor field-effect-transistor (MOSFET) driving circuits. After that, a heat transfer model is implemented using the electrical parameters of the ECM in the next step.

2.2 Parameter analysis-based optimal speed estimation

The first module is the parameter analysis-based optimal speed estimation, as shown in Fig. 2. The heat transfer model is generated considering several parameters for the heat characteristics of the system. To do this, the materials of the LEDs and PCB board, mass, heat level, and total area are estimated. In this case, the room temperature is set to 20 °C, which is fixed in all simulations.

To generate the target model, MATLAB Simulink is used. Specifically, ideal temperature source blocks and convective heat transfer blocks are used, and sensors are connected to fetch system temperatures in real time. In this case, the environmental variables for the LED system model were decided by the parameters extracted from the target LED arrays. Table 2 shows the variables used such as mass and heat transfer coefficients (HTC). First, the initial model for the room temperature environment is generated. The second step is to generate the temperature model with the radiated heat when operating the LED

Table 2. Parameters used in the simulation model

Parameters	Value	Unot
Total power of LEDs	125	W
Mass	0.1	Kg
Specific heat	1005.4	J/kg*K
HTC	200	W/m^2*K
Surface area	1	m^2
Ambient temperature	20	°C
Fan air displacement	0.00015	Kg/rev

Table 3. Fan specifications

Fan specifications	Value
Fan size	80*80 mm^2
Max. speed	1800 RPM
Min. speed	600 RPM
PWM frequency	21~27 kHz

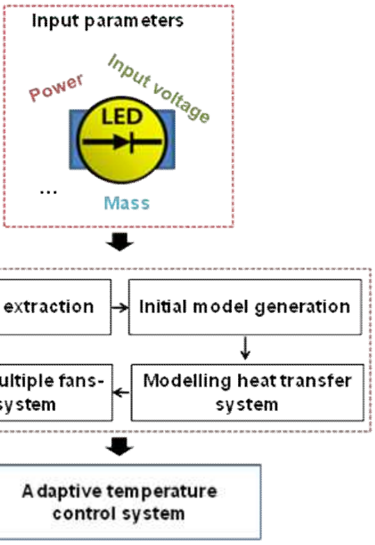


Fig. 4. Block diagram of the parameter analysis-based optimal speed estimation

arrays. Heat source blocks and gain blocks are connected to produce the heat for the LEDs. The final step is to operate the multiple fans connected in the heat source block, thereby modifying the temperature. In this case, to analyze the temperature variation and determine the optimal speed, different speeds of multiple fans are considered.

2.3 Adaptive temperature control system

The second module is the adaptive temperature control, as shown in Fig. 2. Fig. 5 shows that the fans are controlled using a database that contains the optimal speeds given the temperature determined by the previous block. The fan speed stored in the database is one that will maintain the target temperature in the device. Fan specifications are listed in Table 3.

First, the mapped relationship between temperature and fan speed is used in the control system. The proposed system uses an ATmega 2560 microprocessor [7] to generate the control signal. In this system, the fast PWM mode, which generates two interrupts (start and end points) is used. Specifically, the fast PWM mode uni-directionally increases the counter and generates the end point interrupt signal when it approaches the maximum count number TOP. If the TOP value is changed, the PWM frequency can also be dynamically changed, and hence, TOP should be calculated to generate the target PWM frequency. TOP is defined as follows [8]:

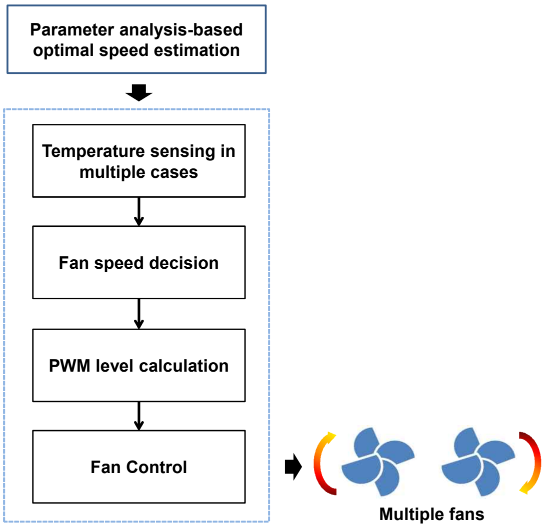


Fig. 5. Block diagram of the adaptive temperature

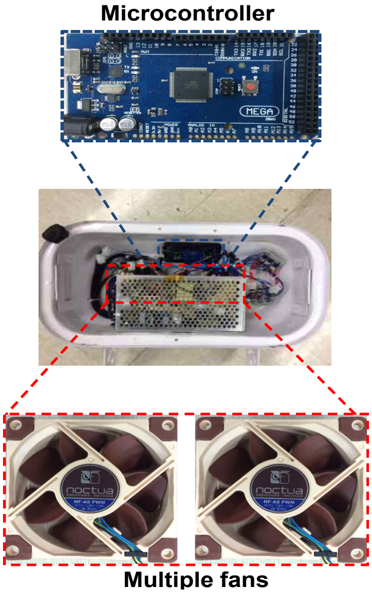


Fig. 6. Prototype of the proposed control system

$$f_{OCnxPWM} = \frac{f_{clk\_I/O}}{N(1+TOP)} \tag{1}$$

$$TOP = \frac{f_{clk\_I/O}}{N \cdot f_{OCnxPWM}} - 1 \tag{2}$$

where $f_{OCnxPWM}$ denotes the target PWM frequency and $f_{clk\_I/O}$ denotes the default frequency of the ATmega 2560 processor. Hence, we can obtain TOP when the PWM mode is operated in the typical mode ($N = 1$).

Next, in order to determine the starting point in the timing diagram, the operation conditions register (OCR) should be determined. If the OCR is determined, the starting point is also known, thereby directly controlling the PWM duty. OCR is defined as follows:

$$OCR_{nx} = \begin{cases} C_{Tmin} \cdot TOP \ , & T_{current} < T_{min} \\ \dfrac{(TOP \cdot T_{current})}{T_{max}} \ , & T_{min} < T_{current} < T_{ma} \\ TOP \ , & T_{max} < T_{current} \end{cases} \tag{3}$$

If the current temperature $T_{current}$ is lower than the lowest temperature bound T_{min}, fan speed is decided by the product of C_{Tmin} and TOP. Constant C_{Tmin} is the minimum speed at which the fan motor can run. It ranges from 0 to 1. If the current temperature is higher than the highest temperature bound, a 100% duty ratio is returned by the following equation. Otherwise, OCR is calculated using the ratio of $T_{current}$ and T_{max}.

3. Experimental results

The performance of the proposed simulation model and implemented prototype system were evaluated. The difference between the simulation model and real system was also calculated. In addition, the proposed system was compared with a conventional LED control system that could not adaptively control the temperature. Fig. 6 shows the prototype of the proposed control system. It consists of 504 LED units, two cooling fans for rapid heat emission, and a protective case. For the control unit, ATmega 2560 microprocessors and MOSFET-based driving circuits were used. We measured temperatures at several vertical and horizontal distances from the middle point of the LED arrays, as shown in Fig. 7(a) (spots 1, 2, and 3). The temperatures at different distances (3 and 10 cm) were measured for 10 min at each spot. The DS18B20 temperature sensor [9], which can be operated from −55 to +125 °C, was used to measure the temperature in real time. The temperature sensor had an error of ±0.5 °C, when the surrounding temperature was from −10 to +85 °C. In

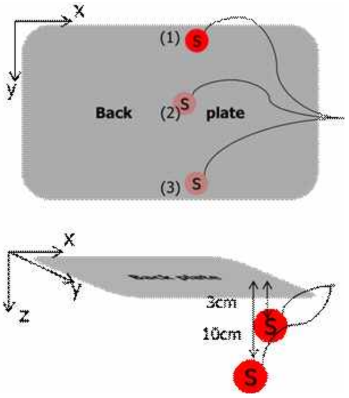
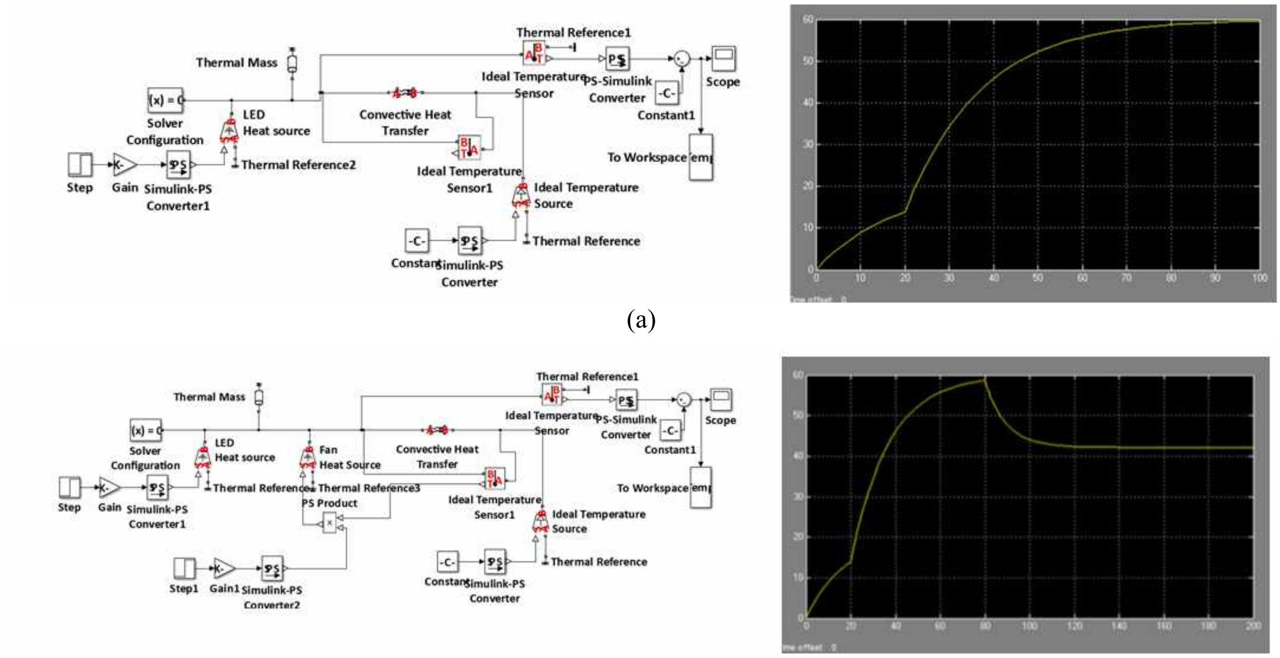


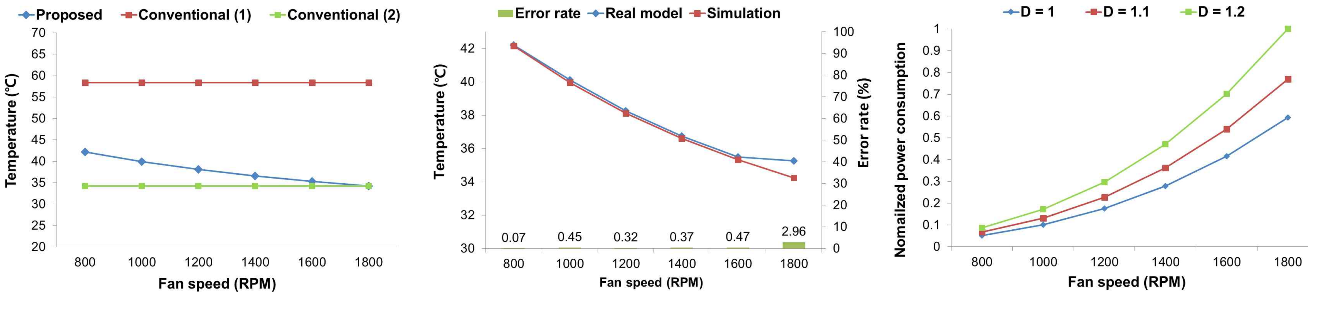
Fig. 7. Temperature measurement positions



(a)

(b)

Fig. 8. Simulink schematics and experimental results: (a) LED system without the proposed temperature control system and (b) LED system with the proposed temperature control system



(a) (b) (c)

Fig. 9. Experimental results at various fan speeds: (a) difference between the proposed and conventional methods in the simulation model (conventional methods (1) without multiple fans and (2) using the maximum fan speed); (b) difference between the simulation model and real system, and (c) power consumption for various fan diameters

addition, the proposed LED system had different brightness conditions (50% and 100% PWM duty cycle). The room temperature was set to 20 °C and used as a reference. A model with heat source blocks to create heat from the LED array was simulated. A block diagram of the model for the LED array device is shown on the left side of Fig. 8(a), and its simulation result is shown on the right side of Fig. 8(a). The average temperature was 58.37 °C when the temperature was steady-state. Finally, the experimental results of the proposed system are shown in Fig. 8(b). The proposed system needed about 80 seconds to attain steady-state. At this point, the fans started to radiate heat. When the fan speed was changed from 800 to 1800 revolutions per minute (RPM), the temperature changed from 42.1 to 35.3 °C.

Using the simulation results, the real LED system prototype was developed to maintain the target temperature. The LED array module was attached to a metal plate and two cooling fans were fixed under the plate. Using this real LED system, we measured the temperatures for different fan speeds and LED brightnesses. In this case, the average room temperature of the experimental environment was 20.2 °C. Fig. 9(a) shows that the conventional method without multiple fans maintained a temperature of almost 60 °C while the conventional method using the maximum fan speed preserved a temperature of almost 35 °C. On the other hand, the proposed system could adaptively change the speed of the multiple fans to maintain the target temperature. In this case, the temperature dropped from 42.7 to 35.93 °C when the fan speed was changed from 800 to 1800 RPM. Fig. 9(b) shows the error between the proposed simulation model and real system. The minimum error of the simulation was 0.07% and the maximum error was 2.96%.

Lastly, we evaluated the temperature and power consumption of the proposed method and conventional method in which the fan speed is fixed to maximum, as is typical when multiple fans are used [10, 11]. In order to understand the relationship between the fan speed and power consumption, the affinity law [12] was used. The normalized power consumption was calculated as follows:

$$\frac{P_1}{P_2} = \left(\frac{N_1}{N_2}\right)^3 \tag{4}$$

$$\frac{P_1}{P_2} = \left(\frac{D_1}{D_2}\right)^3 \tag{5}$$

where P_1 and P_2 denote the power required to rotate the motor, N_1 and N_2 denote the fan speeds, and D_1 and D_2 denote diameters of the fans for the proposed and conventional methods, respectively. According to (4), the power is proportional to the cube of the fan speed. In addition, the power is proportional to the cube of the fan diameter according to (5). In the experimental results, we assumed that the power consumption of a fan motor was normalized from 0 to 1, where 0 is the minimum speed needed to drive the motor and 1 is 1800 RPM, as shown in Fig. 9(c). If we drive the fans at a fixed fan speed of 1800 RPM, the normalized power consumption is fixed at 1, 0.77, and 0.58 when the fan diameter is 1.2, 1.1, and 1, respectively. In addition, the power consumption increased exponentially when the fan speed was increased. Therefore, the proposed control system required 1200 RPM and could reduce the unnecessary power consumption by 60% when compared with the conventional method using the maximum fan speed at a target temperature of 38 °C.

4. Conclusion

This paper proposed a novel LED control system that can adaptively control LED temperature. To achieve this, the proposed method analyzes the LED array temperature and extracts data for the optimal fan speed for different environmental conditions. Based on this data, the optimal control system is implemented. Therefore, the proposed method reduces the fan power consumption and noise compared with the conventional method. In the experimental results, the error between the simulation model and real system was acceptable, and the power consumption of the proposed method was 60% lower than the conventional system when the target temperature was 38 °C.

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