

An Automatic System for Non-Uniform Brightness Compensation of LED Arrays: Image Processing Routines to Locate LED Centers

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ABSTRACT

To be able to accurately study the effect of light on the growth of plants or some living organisms, a light source must be capable of changing its wavelength, brightness and exposure duration. Light Emitting Diodes (LEDs) have many benefits for use in this application. To be applicable, the light source needs to be integrated into a panel consisting of thousands of variable wavelength LEDs. Inside the panel, LEDs normally yield significant variations in brightness of around 15 to 20 % or more unless there is a fine selection of matched LEDs. In this paper, the problems and previously proposed solutions to the variations in brightness of LEDs are addressed and proposed automatic image processing based routines are presented. The routines have been proved to correctly locate the positions of almost all LEDs in the panel.

Keywords: LED illumination, brightness compensation, image processing, brightness uniformity

INTRODUCTION

The proliferation of light emitting diodes (LEDs) has surpassed even the most aggressive expectations. From present-day technologies, such as car headlamps, traffic lights, alphanumeric displays, billboards and large form-factor video displays, to the newest applications, including general and architectural lighting, LCD backlighting, and agriculture applications, the burgeoning acceptance of this light source has fueled the re-design of even the most common devices. As the efficiency and brightness of LEDs improves and the cost decreases, it is anticipated that LED usage will eventually replace conventional lighting methods in consumer applications.

The technology and performance of LED devices continues to improve at rates that exceed expectations [1-3]. These include several declarations of commercial LEDs in the 40 to 50 lumens per Watt (l/W) range, single chip packages of up to 140 l/W, multi-chip packages of 10 l/W and over 300 l/W and new chip records with outputs in the range of 60 to 100 l/W. For agricultural applications, specifically as an energy source for plants [4-9] in a closed system farm and other living organisms [10,11], the light source needs to be integrated with dozens of display panels and thousands of LEDs. Inside each array, LEDs will yield significant variations in brightness, such that the delta in lumens between the brightest and dimmest LED can regularly approach 15 to 20 %. As a result, the difficulties in maintaining quality and maintenance issues need to be solved. Also, as a tool to study the growth of plants under different lighting conditions (wavelength, brightness and exposure duration) which is the main target of our research, a way is needed to compensate for the different brightness of the LEDs during manufacture of the light source and also during experimentations. It is noted that both wavelength and duration controls are out of the scope of this paper. The proposed technique can be used for automatic brightness adjustment of a group of LEDs in an application that requires high quality illumination; i.e. billboards and sign boards.

In order to compensate for the variations in LED brightness, 2 techniques have been employed [1]: first, purchasing of “matched LEDs” from a supplier (also known as “binning”); and second, utilizing a high-quality LED driver with “dot correction” functionality. However, even the matched LEDs from a supplier still have a variation problem in brightness of about 15 to 20 % [12,13]. An approach to compensate for the brightness by elaborate adjusting of an individual LED’s series resistor, which controls the forward current, during the manufacturing process of an LED driver board is also recommended. Using these methods can provide the desired uniformity with minimal design considerations for low-end lighting systems. However, the variance in decay rate, or degradation in brightness, per pixel over time makes this method a short-lived solution. Furthermore, should a defective panel need replacement; the lumen output of the new panel will be visually dissimilar to the others.

Apart from selecting matched LEDs and/or utilizing clever LED drivers with dot correction techniques, Lin and Shieh [14] have proposed using an alternating current (AC) as a source to uniformly drive an LED array in order to compensate for the drop in voltage resulting from parasitic resistance. This approach was used for a backlight in

modern LCD (Liquid Crystal Display) applications. In work by Kuo and Wang [15], a current based bias voltage regulation method was proposed to compensate for the loading effect on an LED array. It was claimed that, with appropriate compensation, the digital scalar controller can provide the bias voltage regulation depending on the loading condition with respect to the ON pixels for each scan line. The proposed approach tried to force each scan line of the LEDs to illuminate at a constant brightness independent of the number of ON pixels. Also, the testing scheme with an appropriate testing pattern was provided in their publication. The most recent publication on the brightness compensation technique specifically applied to RGB billboards as detailed by Boldt and co-workers [12]. The approach relies on incorporating at least one light sensor within each pixel of the display. The sensor is used to provide a measure of the light emitted from each LED representing a primary colour in each pixel. An automatic calibration algorithm running on a personal computer uses this feedback parameter to adjust the PWM (Pulse Width Modulation) to control the corresponding pixel of the display. The drawback of this approach relies on the fact that it requires LED manufacturers to integrate an additional device, a light sensor, to each pixel of the LED's package. This increases the LED's circuit complexity, the overall cost of the system and complicates the maintenance process.

In high-end and high quality display systems, such as billboards for advertising markets and light source to study the growth rate of plants and other organisms, the brightness matching requirements are far more rigid, rendering LED binning insufficient. In order to achieve pixel and panel uniformity over the lifespan of a display unit, manufacturers use advanced LED drivers with "dot correction" capability; i.e. Ti's TLC5940 [16]. Dot correction is a method for managing pixel brightness by adjusting the current supplied to each individual LED in the array. By using the dot correction feature, the processor can control full current to a panel of LEDs while the LED driver scales the current to each LED and creates uniform brightness. As a result, the processor power is free to perform other tasks by eliminating the need to check a look-up table, and by removing complex multiplication tasks for each LED in every refresh cycle. To implement dot correction, the brightness of individual LEDs need to be measured. The dimmest LED in the system is designated as the "base" LED to which every other pixel is matched. To accomplish this calibration, the current supplied to each pixel is multiplied by a fractional value proportional to the LED's lumen output. In many LED drivers, the dot correction value for each LED can be dynamically changed every refresh cycle, or stored inside an integrated EEPROM. This dual-dot correction method offers the flexibility to update overall panel brightness as external lighting conditions change, and provides long term, non-volatile dot correction information that ensures panel uniformity. The EEPROM data can be rewritten as lumen measurements vary over time or as panels fail, requiring correction and replacement, respectively.

In this paper, we present an automatic system to be used in conjunction with an LED array driven by TLC5940 or comparable function drivers. The image processing techniques are employed to analyze the captured image of an LED array in order to automatically locate the centers of all LEDs and directly measure their illuminating

brightness. Alternatively, the LED locations can be used to control the movement of a fibre optic probe of a USB2000 spectrometer to measure the brightness and wavelength of the LEDs. The measuring results, brightness only, are then used to make dot correction within TLC5940 under control of a main controller. The LED array is our own design for use as a tool to study the relationship between the wavelength, brightness and duration of the light source on the growth of plants and other living organisms. In the next section, the proposed automatic solution to this problem is given.

MATERIALS AND METHODS

With the limitations and difficulties of using the conventional approaches and the hardware complexity involved in employing the previously presented solutions, we propose an alternative automatic solution. First of all, we briefly introduce the target LED array, the related instrument and the system setup.

The Target LED Array

The presented approach in this paper is the one being utilized to calibrate the non-uniform brightness of our own designed LED array. For this application, as a study tool, its brightness needs to be correctly calibrated. In addition, its wavelengths need to be recorded. For other applications, only brightness levels are required to be adjusted with similar system setup and procedures.

Figure 1 illustrates a single module of the LED array consisting of 44 lamps with variations in illuminated wavelength. In addition, due to the different sources and manufacturing batches of LEDs, the brightness levels of the LEDs are very far from uniform. Also, from the application's point of view, the standard dot matrix LED array commercially available is unusable in this case as several wavelengths are required. It can be seen that the LED positions are fairly far from perfect, both individually and from module to module, as a result of the assembly process.

All LEDs in the module are driven by TLC5940 on a separated board. A group of TLC5940s are, in turn, controlled by a single microcontroller via an SPI (Serial Peripheral Interface) protocol. The main responsibilities of the microcontroller are to update the dot correction value, control the brightness and duration of the selected LEDs and switch on/off LEDs under user control. It is noted again that while the target LED arrays in our experiment were fixed to be our own designed ones, the approach is general and can be extended for use in other similar applications.



Figure 1 A single module of an LED array consisting of 44 lamps with variations in illuminated wavelengths and brightness levels.

The Required Instruments and System Setup

In order to measure the brightness of the LEDs with a high degree of correctness, a USB2000 spectrometer (Ocean Optic Inc., USA) was employed. The spectrometer is fairly flexible to be used as it comes with a fiber optic probe to connect between the light sources and its internal sensor. To be able to move the fiber optic probe to a specific position of the LED array in this application, an XY scanner needs to be used. Alternatively, for an application that requires a moderate degree of correctness and only brightness is required, the captured image from a digital camera can be used for analysis. For the latter system setup, the captured image then serves 2 purposes: for LED position analysis and for measuring the brightness at the center of the LEDs. In our implementation, the latter system setup was selected as it eliminates the requirement to install an additional XY scanner.

The proposed approach relies on acquiring the RGB image of an LED array. During the course of our experiments, all of the still images were acquired using a single CCD (Coupled-charge Device) color camera (XC-711, Sony, Japan) with a zoom lens of 12.5 - 75 mm focal length (C6Z1218, Cosmicar), an image grabbing and processing board (Meter, Matrox Inc., Canada), and a personal computer (Intel Pentium 4 processor, 2.4 GHz). The CCD color camera was fixed at a position of 1 m above an LED array sample and was set to focus on the surface of the sample. A visible full spectrum light source used during our experiments was the GE Sunshine Starcoat[®] T8

(F15T8/SUN 6PK) light bulb. It was installed to illuminate from a distance of 1 m away with an angle of 45 degree with respect to an LED array. All the ambient light effects were eliminated by enclosing the visual system within a black box. The Matrox Imaging Library (MIL 7.5, Matrox Inc., Canada) was linked to the programs to grab RGB color images of 760×760 pixels. The CCD camera was employed for image acquisition with 4,150 lx and F4.0 opening (iris diaphragm). Images were stored in the hard drive from the format of the camera into JPEG file format.

For a single calibration, 2 different images are taken of a single LED array. The first image is taken under 2 conditions: (1) all LEDs are turned off and (2) the external light source is turned on. It is used to automatically locate the LED positions with the approaches to be presented in the next section. The second image is taken while all LEDs are turned on at their highest brightness while the external light source is turned off. This image is used for brightness measurement.

The Image Processing Routines

The software tool used during the course of our development of the proposed automatic system was Matlab 7.0. Our preliminary studies gave rise to the conclusion that the standard image processing routines [17] successfully applied to similar problems; i.e. object recognition, detection or colour segmentation, failed to locate all the LED positions. This could perhaps result from the variety of colours of the LED packages. In addition, as the normal LED packages are partially transparent (as clearly seen in **Figure 1**), it results in failures to segment between objects and objects and background. The most difficult task we encountered was that the light gray package LEDs were likely to be removed from the transformed image. As a result, the standard image processing routines fail to locate this group of LEDs.

Figure 2 presents the proposed image processing routines that have been successfully tested on the images of LED arrays. With respect to **Figure 2**, the input to the proposed image processing routines is the RGB image of an LED array. Two independent processes are then applied to the input image. The processes on the left side are responsible for extracting the light gray package LEDs which are likely to be removed by utilizing the standard image processing routines. The right side processes are responsible for extracting other package colours. Both resulting images are converted to black and white versions and all the internal holes are filled. It is worth noting here that the internal holes of LEDs are the result of the semi-transparent nature of their packages. That is to say we can partially look through the package to see the inside components. These components together with the response of the round shape package to the light source make the inside package colour somehow differ from the colour at the edge.

Both intermediate black and white images are then added together in order to produce the resulting image which seems to grab all the LEDs in the array. The image is then inverted to be ready for a boundary detection process which gives rise to a set of points at the boundaries of all LEDs; $B(i)$ where i is the index of an LED. The final process retrieves a set of boundary points $B(i)$, whose members are greater than a pre-

defined number (100 in our case), one by one and applies the smallest enclosing circle (SEC) or minimal enclosing circle (MEC) algorithm on it [18-20]. It is noted that we avoid processing $B(i)$ with less than 100 members because it is likely that the previous algorithm can successfully find more than 100 boundary points for a normal LED. The SEC/MEC algorithm is, simply stated, the algorithm to find the smallest circle that completely contains a set of points (LED's boundary points in this case) [21]. Formally, given a set S of n planar points, find the circle C of smallest radius such that all points in S are contained in either C or its boundary. The final results of the algorithm are the centre and radius of all LEDs in the image.

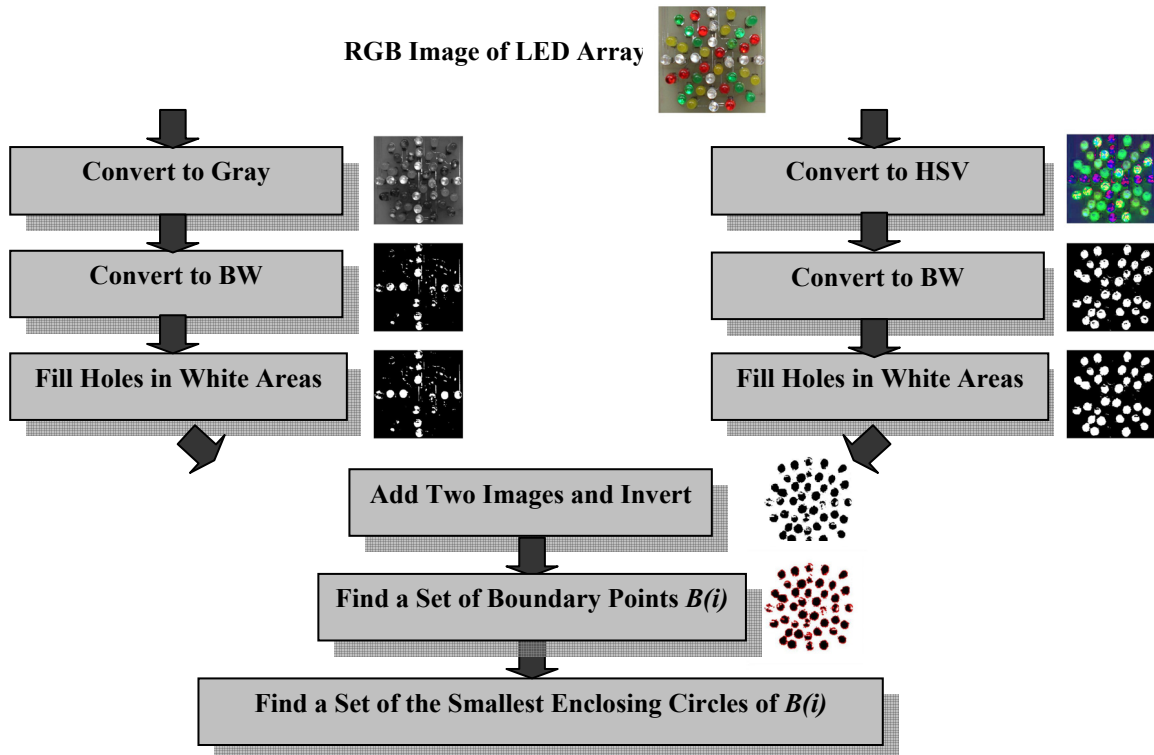


Figure 2 The proposed image processing routines to automatically locate the center of LEDs.

It is further noted that the processes to produce both black and white counterparts still required some user intervention. This is performed in order to set the level at which all background and unwanted defects; i.e. internal holes and background resulting from a non-uniform illumination, within the images are removed as much as possible. In addition, the manual removal of some imperfections in the intermediate image resulting from adding the images from the left and right sides is required.

Software Implementation of the Proposed Routines

The proposed image processing routines detailed in the previous section were implemented on a personal computer in order to verify their functional correctness. Matlab version 7.0 was mainly used as a software development tool. The developed application running on the Windows XP machine is responsible for retrieving the RGB image of an LED array, producing the intermediate images following the proposed routines and supporting appropriate user interventions to adjust the black and white levels and remove defects. The final outcome image is also displayed by the application. **Figure 3** shows the screen capture of the application as a whole.

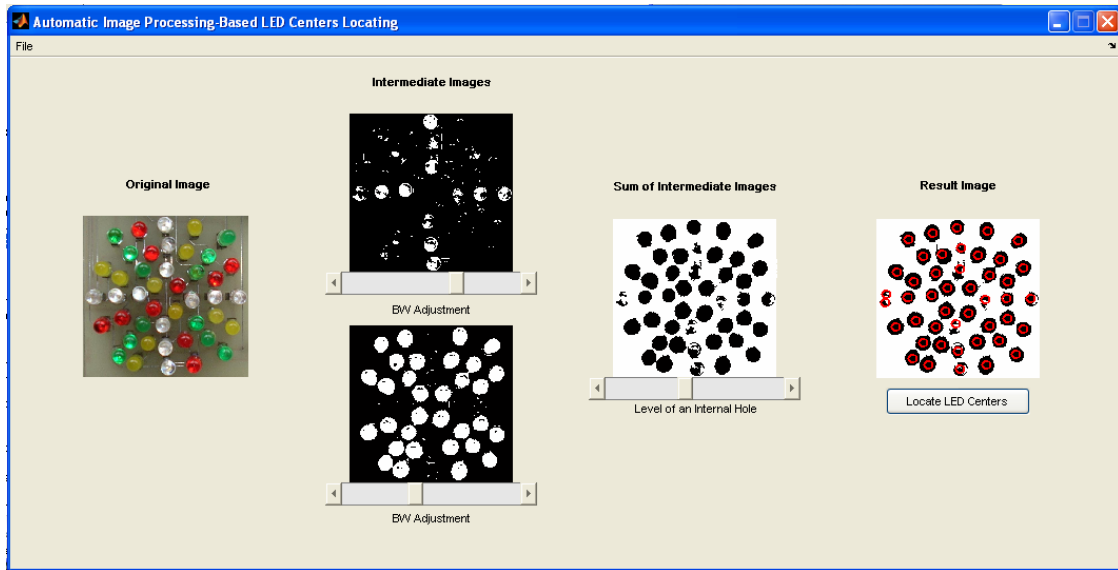


Figure 3 The screen capture of the application to locate the center of LEDs.

RESULTS AND DISCUSSION

As seen in **Figure 3**, it is obvious that the proposed routines are correctly capable of finding the LED centers with some observable failures. During the course of our experiments, we tested the correctness of the routines with respect to different input images captured from several LED arrays. Due to the fact that some intermediate images were manually adjusted during processing in order to remove the defects and improve their quality before locating LED centers, it was then difficult to measure exactly the percent correctness. To reflect the operational correctness, the results presented here were produced without any manual adjustment to the processes on the right side of **Figure 2**. The allowable adjustment to the processes on the left side was only to remove all background caused by a non-uniform illumination. Some results are illustrated in **Figure 4**.

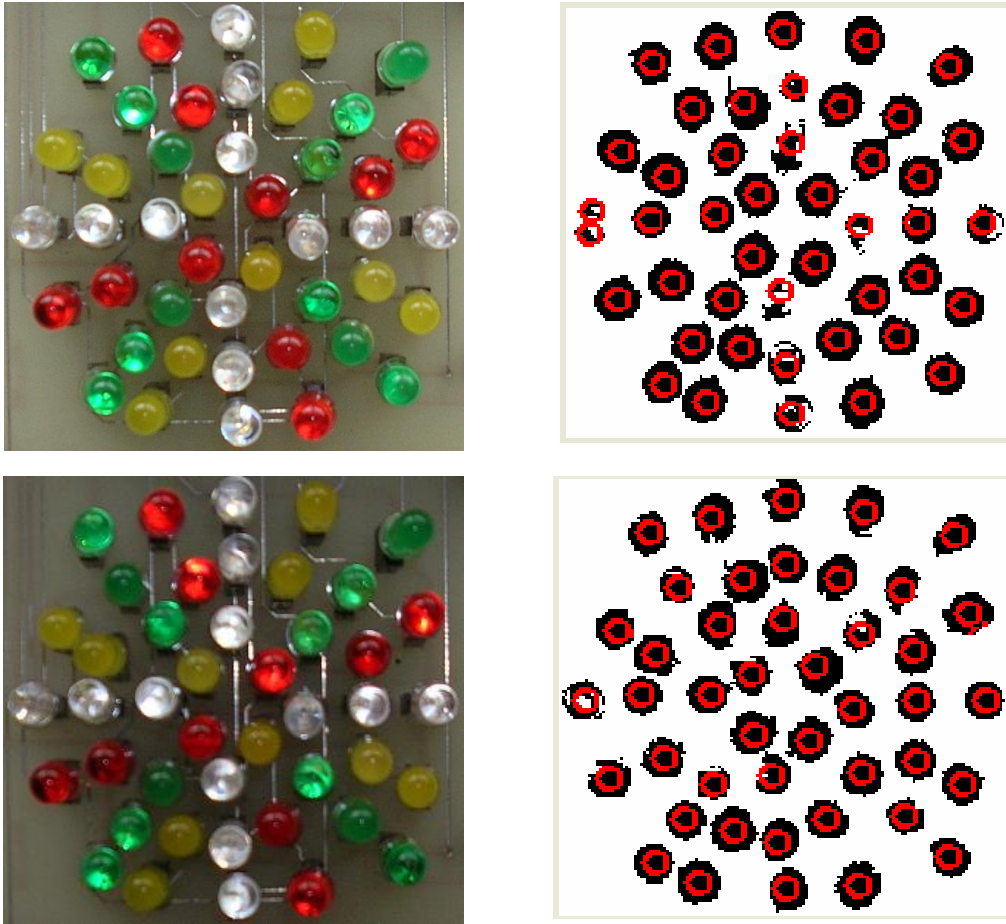


Figure 4 Two original images and the images overlaid by the resulting center of LEDs.

Consider the first result in **Figure 4**, it reveals that the routines could correctly locate the center of 43 out of 44 LEDs. This is equivalent to 97 percent of correctness. The LED on the left side along the horizontal center line was incorrectly located due to the fact that its covering region on the image was split up in to 2 clusters. Notice that although several regions of LEDs in the image seem to have imperfect shapes, they were located correctly as far as all the regions were connected. The lower images in **Figure 4** shows the result when a covering region of the LED on the left side along the horizontal center line has an interior hole. Although, the hole can be removed by carefully adjustment of the black and white threshold, doing so could result in deteriorating the quality of the rest of LEDs. Surprisingly, without removing the internal hole, the routines can successfully locate the center of the LED. By performing the routines with similar allowed procedures for manual adjustment mentioned above on a set of 50 images of an LED array, we have found that the maximum, minimum and average percents of correctness are 100, 63, and 94, respectively. The minimum one

was found when most LEDs on the image have a light gray package colour. The correctness for these images can be leveraged by making manual adjustment to the intermediate images.

Figure 5 shows the result of using the routines to identify the center of all LEDs, measure and display the brightness at those points. The latter 2 processes were performed without an external light source and under the condition that all LEDs were switched on to their brightest level. The application was also developed to have a feature to uniformly adjust the brightness and transfer the final value to the microcontroller of an LED array. An XY scanner to control the spectrometer is being developed in order to accept a set of center coordinates from this application and make more accurate measurements.



Figure 5 The result of using the routines to identify the center of all LEDs, measure and display the brightness levels.

CONCLUSIONS

Since LEDs are used in many applications; i.e.: as an artificial light source in the agricultural field. In doing so, the light source needs to be integrated into a panel consisting of thousands of variable wavelength LEDs. Inside the panel, LEDs normally yield significant variations in brightness around 15 to 20 % or more unless the LEDs are finely selected and matched, in term of brightness, which is a costly and time-consuming process. The previously proposed solutions to the variations in brightness of LED arrays were reviewed. We found that the automatic solution to calibrate the LED brightness had not been mentioned in detail. Due to the nature of the objects to be detected and measured, the standard image processing routines could not be correctly applied. With these limitations in mind, the proposed image processing based solution was given. The verifying results showed that even without human intervention, the routines could correctly locate the LED positions. In the current version of the system, the positions were then used to measure the LED brightness when all LEDs were switched on at the highest level of brightness. The measuring results were used to uniformly adjust the brightness value and sent back to the microcontroller of the LED array board. The alternative solution proposed in this paper was to transfer the set of LED positions to an XY scanner connected to a fiber optic based spectrometer (i.e. USB2000). This could leverage the accuracy of measurement.

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บทคัดย่อ

วัฒน์พงศ์ เกิดทองมี และ เตาทิพย์ หล้าสูบ

ระบบอัตโนมัติเพื่อปรับความเข้มแสงที่แตกต่างกันของกลุ่มหลอดแสดงผลชนิดไดโอดเปล่งแสง: กระบวนการประมวลผลภาพเพื่อหาตำแหน่งของหลอดแสดงผล

ในการประยุกต์ใช้งานเพื่อศึกษาผลของแสงที่มีต่อการเจริญเติบโตของพืชหรือสิ่งมีชีวิตอื่นๆ แหล่งกำเนิดแสงจำเป็นต้องมีขีดความสามารถในการปรับเปลี่ยนความยาวคลื่น ความเข้มและระยะเวลาของการเปล่งแสงได้ หลอดแสดงผลชนิดไดโอดเปล่งแสงมีข้อได้เปรียบสำหรับประยุกต์ใช้งานด้านนี้ ในการจัดสร้างแหล่งกำเนิดแสงโดยใช้หลอดแสดงผลชนิดไดโอดเปล่งแสงจำเป็นต้องใช้หลอดแสดงผลจำนวนมากและหลากหลายความยาวคลื่นมาประกอบเข้าด้วยกัน ข้อจำกัดพื้นฐานของหลอดแสดงผลชนิดไดโอดเปล่งแสงคือ ความแตกต่างของความเข้มแสงที่ได้ซึ่งอยู่ในช่วงระหว่าง 15 - 20 เปอร์เซ็นต์หรือมากกว่าหากมิได้ผ่านขั้นตอนการคัดเลือกมาเป็นอย่างดี ในบทความนี้ ผู้วิจัยได้นำเสนอปัญหาและแนวทางการแก้ไขความแตกต่างของความเข้มแสงของกลุ่มของหลอดแสดงผลชนิดไดโอดเปล่งแสงที่นักวิจัยอื่นๆ ได้เคยนำเสนอ และนำเสนอแนวทางใหม่ที่ใช้เทคนิคการประมวลผลภาพเพื่อสร้างระบบอัตโนมัติในการปรับความเข้มแสงของกลุ่มหลอดแสดงผลชนิดไดโอดเปล่งแสงให้คงที่แนวทางที่ได้นำเสนอนี้ได้รับการทดสอบแล้วว่าสามารถระบุตำแหน่งของกลุ่มของหลอดแสดงผลชนิดไดโอดเปล่งแสงได้อย่างถูกต้องเพื่อนำไปสู่การวัดค่าและปรับค่าความเข้มแสงต่อไป