Image-like illumination with LED arrays: design

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Received September 7, 2011; revised December 13, 2011; accepted December 13, 2011;
posted December 13, 2011 (Doc. ID 154190); published February 22, 2012

An array of spatially distributed light-emitting diodes (LEDs) can produce an illumination pattern that approaches an image by individually modulating each LED. In this letter, I analyze the first-order design of such systems in order to achieve the best match between the illumination distribution and a desired image. In particular, simple formulas are given for the optimal number of LEDs, working distance, array size, and LED beam pattern. The analysis developed here may be applied to the design of LED systems such as architecture lighting, energy-efficient lighting, backlight local dimming for displays, and structured illumination microscopy with micro-LED arrays.

OCIS codes: 150.2950, 330.5000, 120.5630, 230.3670, 220.2945.

When we think about illumination, a uniform light distribution usually comes to mind. However, the unique controllability of LEDs is adding new dimensions of light utilization [1]. This illumination controllability is maximized by the possibility of lighting systems to be formed by a large number of spatially distributed LEDs. By switching and dimming each LED, one can adaptively create a nearly infinite variety of illumination patterns (see Fig. 1). In other words, an LED array can easily direct light emission into highly structured lighting patterns without additional optical devices by simply modulating each LED individually.

This type of illumination has many applications but lacks a unifying name. I call it "image-like illumination" since such light distributions may approximate a desired image. One application is the smart light distribution for energy-efficient illumination in working and living spaces [2,3]. Decoration, entertainment, and relaxation applications may benefit as well. For example, imagine an illuminated ceiling showing dynamic quasi-image patterns and, even more, color images by using a RGB LED array. Another application is to provide high contrast for large screen displays with direct backlighting, where the local dimming of LEDs provides an image-like illumination that significantly increases the image contrast and reduces the light leakage in image regions not requiring illumination [4,5]. An interesting application is in microprojection devices, which have many individually addressable micropixel LEDs that directly project structured light distributions into biological cells, tissues, and photoresists [6].

In all of these applications, it is necessary to closely match the illumination distribution with a desired image or arbitrary pattern. This match depends on the LED array design, which raises four important questions: How many LEDs should be used? How far from the illumination plane should the array be placed? How big should the array be? And what type of LEDs should be used?

In this letter, empirical formulas are numerically found for the optimal: number of LEDs, working distance (see Fig. 2), array size, and LED beam pattern.

Several steps were required to perform this task (Fig. 3). First, given a desired image, a numerical algorithm determined the LED intensity levels that most closely approximate the illumination pattern to the image. There are several methods to determine the optimal LED intensities [2–5,7]. I used a constrained least squares method because, although not the fastest method, it gives the best match between the image and the illumination pattern [7]. After this step, the image-like irradiance pattern was simulated and compared with the target image. The similarity between them was assessed by means of the root-mean-squared (rms) difference [8]:

$$\Delta_{\mathrm{rms}} = \sqrt{\frac{1}{k-1}\sum_{i,j}^{k}\left(\frac{P_{ij}-I_{ij}}{I_{\mathrm{ave}}}\right)^2}, \quad (1)$$

where P is the illumination pattern and I is the target image. I_{ave} is the mean of I, and k is the number of image pixels. To avoid boundary artifacts, the illumination pattern was delimited to the area covered by the LED array. I performed the calculations in the space of the target image, converting the illumination pattern to one image of equal size [7].

The Δ_{rms} was calculated for several working distances. The smaller the rms difference, the higher the similarity between the image and the illumination pattern. From Δ_{rms} versus s, the optimal working distance was defined as the distance at which Δ_{rms} was minimal. The calculations were repeated with different numbers of LEDs (from 7×7 to 25×25 LEDs) and/or different LED array sizes. After hundreds of computations, the optimal

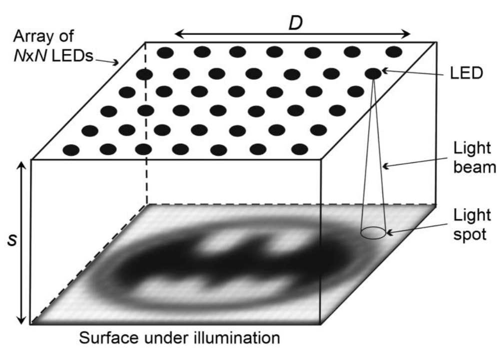

Fig. 1. LED array producing an image-like illumination by modulating the intensity of each LED. Here s is the working distance, $D\times D$ is the array size, and $N\times N$ is the number of LEDs. Batman logo is a trademark of DC Comics and is used with permission.

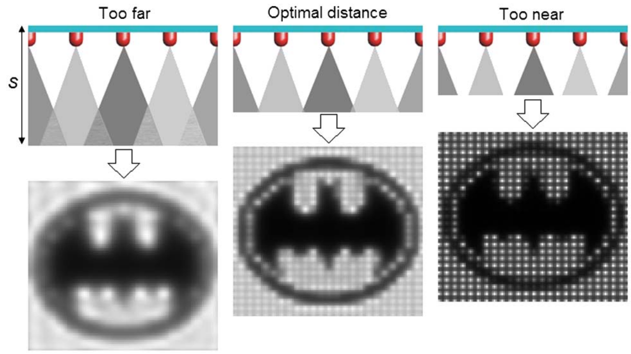

Fig. 2. (Color online) Concept of optimal working distance. If distance s is too long, the light pattern is blurred; and if it is too short, the pattern becomes a hot-spot distribution. Note that LEDs are modulated with the optimal intensities that require each of these three working distances. Batman logo is a trademark of DC Comics and is used with permission.

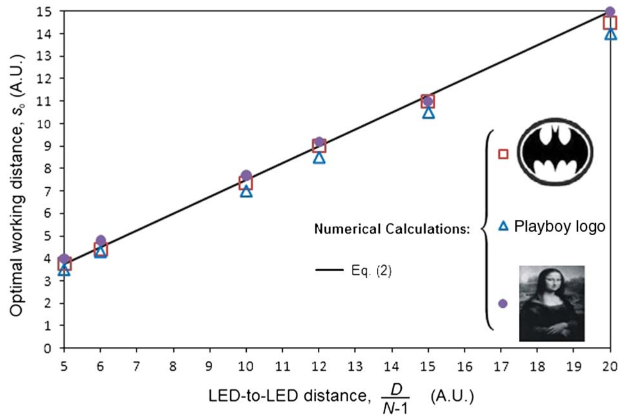

Fig. 4. (Color online) Optimal illumination distance in function of the separation between two adjacent LEDs. Shown here are the linear fitting [Eq. (2)], and numerical results using three different target images. Each numerical point is obtained using the method described in Fig. 3 for Lambertian LEDs. Batman logo is a trademark of DC Comics and is used with permission.

working distance, the optimal number of LEDs, and the optimal array size were found. At the early stage of this work it was difficult to find a suitable mathematical model to establish the relationship between these parameters [7]. First, I tried to relate the working distance with both the "total" number of LEDs and the area of the LED array [7]. After improving the early methodology, and after several attempts, it was finally solved by using the conceptual framework of [9], where the condition for uniform illumination is a linear relationship between the working distance and the LED-to-LED spacing. Figure 4 shows the condition for optimal image-like illumination. It is interesting to note that this relationship is practically independent of the spatial structure of the target image. Three different images were used as target images: the logos of Batman and Playboy, which have high contrast and simple spatial structure; and the Mona Lisa painting, which has complex spatial structure.

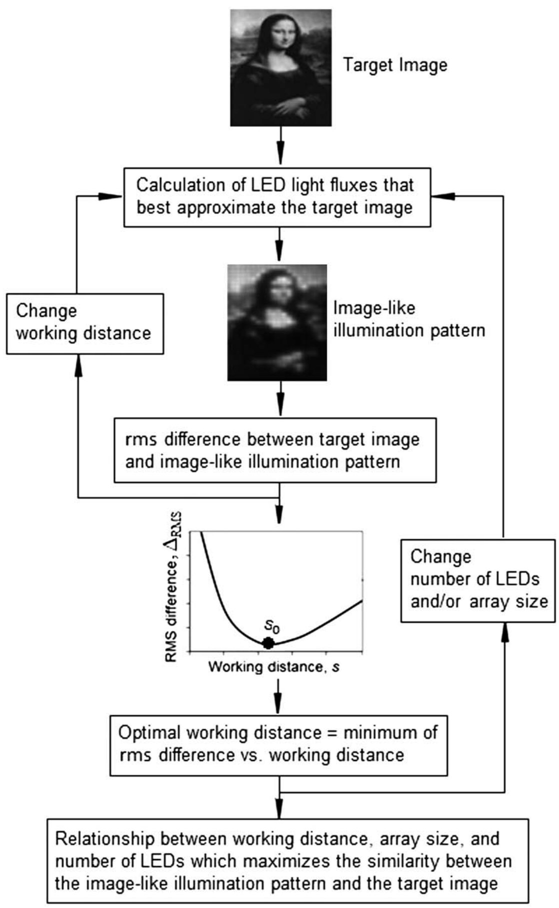

Fig. 3. Methodology used to find the optimal relationship between the illumination distance, LED array size, and number of LEDs. In this letter I consider only square grids (Fig. 1).

By fitting the results of the calculations (see Fig. 4), I have determined a set of simple empirical formulas for the LED array design. Using Lambertian LEDs, the optimal illumination distance is

$$s_o = \frac{3}{4}\left(\frac{D}{N-1}\right), \tag{2}$$

where the size of the LED array is $D \times D$ and the number of LEDs is $N \times N$. For example, if using 10×10 LEDs in a 500×500 cm^2 array, the optimal working distance is 42 cm. Equation (2) is also valid for a rectangular array of LEDs with $D_x \times D_y$ and $N_x \times N_y$, because the important parameter is the distance between LEDs, so Eq. (2) can be evaluated by using only D_x and N_x, or D_y and N_y.

Similarly, given s and N, one can obtain the optimal array size $D_o \times D_o$ from Eq. (2), where $D_o = 4/3(N-1)s$.

It is also important to determine the optimal number of LEDs. It is a common design condition to fix both the working distance and the array size. This then raises the question of how many LEDs to use. An array of $N \times N$ LEDs has an optimal N given by

$$N_o = \mathrm{round}\left(\frac{3D}{4s}\right) + 1, \tag{3}$$

where "round[c]" is c rounded to the nearest integer. If the array is rectangular, the optimum LED number can be obtained by calculating N_x using D_x and N_y using D_y.

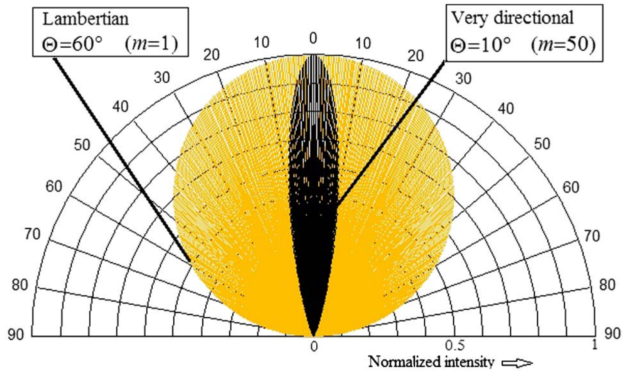

Fig. 5. (Color online) Radiation pattern of an LED with the cosine-power model [10]. Here Θ is the half-width at half-maximum (HWHM) angle.

Although Lambertian emission could be the most common radiation pattern in modern LEDs, narrower beam emitters may be useful for image-like illumination [9,10]. To find the design formulas for LEDs with any beam directionality, many calculations were performed, modeling LEDs with different light beams. For simplicity, the angular intensity distribution was modeled with $I(\theta) = I_0 \cos^m \theta$, where θ is the viewing angle and m is the directionality (Fig. 5). To find the fitting function, once again I used the same mathematical representation as that in [9], finding a perfect fitting function for the optimal working distance, given by

$$s_o = \frac{\sqrt{4m+5}}{4}\left(\frac{D}{N-1}\right). \quad (4)$$

Here $m = -\ln 2/\ln(\cos\Theta)$, where Θ is the half angle (Fig. 5). Equation (4) reduces to Eq. (2) for $\Theta = 60°$ or $m = 1$. Conversely, given the working distance and the array size, the optimal number of LEDs $N_o \times N_o$ is obtained from

$$N_o = \mathrm{round}\left(\frac{\sqrt{4m+5}}{4}\frac{D}{s}\right) + 1. \quad (5)$$

Another possible situation is that in which all setup parameters are given, and the LED light beam is required to calculate [11]. The optimal HWHM angle of the radiation pattern of LEDs is

$$\Theta_o = \arccos\left\{2^{-\left[\frac{4D^2}{[4s(N-1)]^2 - 5D^2}\right]}\right\}. \quad (6)$$

For example, if using 21×21 LEDs in an array of $15 \times 15\ \mathrm{m}^2$, with a working distance of 2.5 m, the optimal directionality of LEDs should be $\Theta_o = 10°$.

In summary, using Eqs. (2)–(6) minimizes the rms difference; i.e., the LED array achieves the best image-like illumination. However, there are three additional design aspects that merit comment. First, the similarity between the illumination pattern and the target image depends on the density of LEDs; i.e., the minimum Δ_{rms} increases approximately linearly with the LED-to-LED separation. Second, unlike Eqs. (2)–(6), the absolute value of Δ_{rms} depends on the spatial structure of the target image. Third, Eqs. (2)–(6) are approximate if the light pattern is for humans, because Δ_{rms} is not a vision-based metric [12].

In conclusion, I have analyzed the optical design of LED arrays that produce image-like illumination. From many numerical computations, simple formulas were deduced for the optimal number of LEDs, working distance, array size, and LED beam pattern. These design equations ensure that the LED array approximately achieves the best match between the irradiance pattern and the target image. Further work may include the following: the analysis of the effect of using LEDs with complex radiation patterns [10]; the design of three-dimensional LED arrays [13]; and the incorporation of visual effects [12,14].

This research was supported by CONACYT grant 128452. I thank Maureen Sophia Harkins for proofreading this paper.

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