A Design Method for LEDs Arrays Structure Illumination

Fupei Wu, Shengping Li, Xianmin Zhang, and Weilin Ye

***Abstract*—Capturing high quality image is very important in the active automatic optical inspection system. Besides camera, image quality mainly is affected by the illumination. A design method of structure illumination, which is comprised of light emitting diodes (LEDs) arrays, is proposed in this paper. And especially, these LEDs arrays are not in the same plane. First, the single LED irradiating model is built based on analyzing its irradiance properties. Second, the case of two LEDs irradiating is set as an example to analyze superposition properties of the same color light for any specified point's light brightness based on the built single LED irradiating model, and then the irradiating model of LEDs is developed. Third, the structure illumination design method of LEDs ring arrays is illustrated based on the proposed design model of illumination uniformity. Especially, the illumination design method is decomposed into two subproblems to simplify the design process, which can reduce the design difficulty. Experimental results show that the light intensity deviation is less than 3.78% by the proposed illumination design method, which validates the effectiveness of the proposed method.**

***Index Terms*—Automatic optical inspection, image analysis, light emitting diodes, lighting, machine vision.**

I. Introduction

CAPTURING high quality image is a critical part in visual inspection system because the acquired image quality will affect the design of inspection algorithms due to image processing cost, and will also affect the accuracy and reliability of the visual inspection system. In the active visual inspection system, the object information and the background information in the inspected image can be separated accurately by the precise illumination structure design [1]–[3]. Usually, different inspected objects need different visual illuminations in order to highlight the object information and the background information clearly. Therefore, the illumination design method is also different because of detected objects' variety [4]–[5]. Monocular vision inspection system commonly uses structure illumination, which is used to detect complex objects, especially micro objects, such as solder paste quality of printed circuit boards (PCBs), mounted quality of electronic components, solder joint quality of PCBs and so on. In these inspection process, special illumination structure usually be used to map the object information as much as possible into a color image and to highlight the object information and the background information fairly [1]–[5].

Light emitting didodes (LEDs) arrays illuminations have been used widely in automatic optical inspection system (AOIs) because of LED's excellent performances, such as fast response, long lifetime, low cost, adjustable brightness, configurable structure and easy heat dissipation [1]–[5]. Because of varieties of inspected objects, LEDs arrays illumination is designed into a unique structure correspondingly, such as circular shape, ring form, rectangle shape, linear shape, planar shape, noplanar shape and so on. For example, the linear structure LEDs array illumination is used in the linear scanning AOIs and the LEDs ring arrays structure illumination is used in the monocular vision inspection system [6]–[8]. Furthermore, in order to obtain an ideal illumination, it usually need to design the unique structure, which is comprised of LED arrays. In other words, the performances of LEDs will play a critical role to decide the illumination structure. Recently, there are many works in researching LEDs performances in literatures. An indirect design method of the uniform illumination is proposed by a mathematically simulated algorithm [9], and the three-ring LEDs array is considered for the sphere's inner surface. In addition, an uniform illumination design method is presented for the diffuse reflection freeform surface [10], and its simulation result shows that the irradiance uniformity of the detection plane is above 95%. In order to improve the luminous efficiency for the uniform illumination, Zhu *et al.* [11] present a design method of diffuse reflection free-form surface containing the energy conservation. Experimental results show that it is a feasible method to improve the illumination uniformity. The problem of rendering uniform illumination is studied by a regular LED array on the ceiling of a room [12], and a cost function is proposed to measure the uniformity of the realized illumination pattern and a mathematical framework is presented to design a LED illumination system. Some of LEDs can be saved for the same degree of uniformity by this method. The problem of designing uniform illumination is studied too by Moreno *et al.* [13] and Whang *et al.* [14]. They mainly focus on the case of LEDs lying in the same plane. The measurement of averaged LED intensity was studied in the impact of detector spatial uniformity [15] and several reasons which result in the significant measurement errors were analyzed. And a silicon-based LED packaging module with integrated RGB color sensors was developed in [16]. It can detect the variations in the brightness and specified wavelength intensity of white LEDs to evaluate the chromaticity and color temperature of emitting light in real time. A new

Manuscript received August 7, 2015; revised April 11, 2016; accepted July 19, 2016. Date of publication July 21, 2016; date of current version September 13, 2016. This work was supported in part by the National Science Foundation of China under Grants 51305247, 61307124, and 61573233, and in part by Guangdong Innovation Program 2015KTSCX038.

F. Wu, S. Li, and W. Ye are with the Department of Mechatronic Engineering, Shantou University, Shantou 515063, China (e-mail: fpwu@stu.edu.cn; spli@stu.edu.cn; wlye@stu.edu.cn).

X. Zhang is with the School of Mechanical and Automotive Engineering, South China University of Technology, Guangzhou 510640, China (e-mail: zhangxm@scut.edu.cn).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/JDT.2016.2593770

approach to control the white color point of the red/green/blue LED in all aging states was proposed in [17]. In this reference, the proposed method can avoid the color point to go out of regulation by adjusting the color set points. Because of LED's nonlinear I-V characteristics, Modepalli and Parsa presented a dual-purpose offline LED driver with illumination control and visible light communications [18]. It realized a constant current source by a buck converter without a capacitor using average current mode control. On the other hand of LEDs application, Yang [19] developed a method to improve the performances of backlight modules. it employed LEDs with freeform secondary optical lens as a lighting source to integrate and manipulate the specially designed and optimized 3D-like pattern distribution of the micro features to obtain the required optical characteristics at maximal performance. And it can improve the performance of brightness, thickness and uniformity obviously. Phandharipande and Caicedo presented an algorithm for centralized and distributed LEDs lighting control to achieve a balance between power minimization and user satisfaction with the rendered illumination of LEDs under a localized illumination rendering strategy [20]. In addition, an illumination-robust optical flow method is designed in [21] based on a stochastic technique, and reflectance is given higher weight to ensure robustnessagainst illumination.

However, how to design and optimize a structure illumination of LEDs arrays is few reported in literatures, in which the relationship of the irradiance model of LEDs and the illumination structure need to be analyzed and parameterized because these LEDs arrays aren't in the same plane. Importantly, structure illuminations comprised by LEDs arrays are extensively used in AOI.

Based on LEDs irradiance characteristics, the design problem of mono-color structure illumination is analyzed and the designed method about this illumination is given in this manuscript. It can meet the expected objectives in brightness and uniformity within the pointed field of view.

This paper is organized as follows. The model of LEDs irradianceis analyzed in Section II, which includes the shape analysis of the LED light spot. The same color light superposition properties with two LEDs irradiating is developed in Section III. And then the design model of mono-color structure illumination is built in Section IV. Next, experimental results are presented and analyzed in Section V. Finally, some conclusions are reported in Section VI.

II. The Model of LED Irradiance

The shape of a LED lighting spot will be analyzed especially in this section and it will be used to design the structure of LEDs arrays illumination. The red color LEDs produced by Nichia are set as an example in the analyzing experiment. As shown in Fig. 1, the LED irradiates to the horizontal plane and its distance is set as h, then a circle-like light spot is shown in the plane.

As shown in Fig. 1, the strongest brightness lies in the center of the light spot, and the brightness is gradually decreasing along the radius direction. So it can be supposed as the model shown in Fig. 2. Supposing the radius of the circle-like light spot is

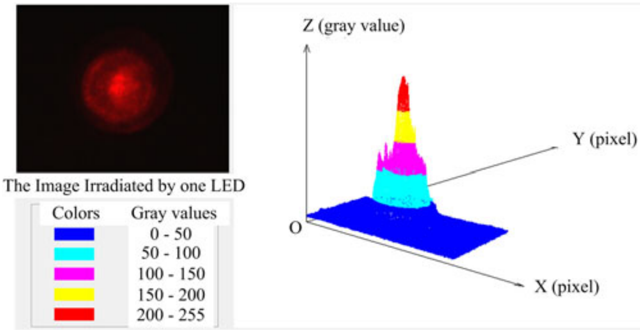


Fig. 1. The light spot of the single LED.

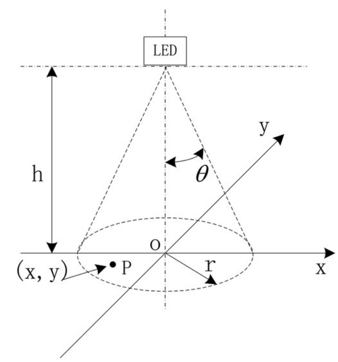


Fig. 2. The model of single LED irradiating.

r, then the irradiance angle can be expressed as $\theta = \arctan \frac{r}{h}$. Consequently, the brightness of any one point P within the spot will be decided by the irradiance vertical distance h of LED and the distance between the inspected point P and the center of the light spot. If setting the coordination system based on the centre light line of LED light spot, shown as in Fig. 2, and then, under the irradiance of one LED, the brightness of any one inspected point $P(x,y)$ can be expressed as

$$I_{p(x,y)} = I_C \cdot L(h, \sqrt{x^2+y^2}) \cdot \alpha(h) \cdot \beta(h \tan \theta_p) \tag{1}$$

and

$$\theta_p = \arctan \frac{\sqrt{x^2+y^2}}{h} \tag{2}$$

where I_C is the value of the center brightness, $h \tan \theta_p$ is the distance between the inspected point P and the center of the light spot, θ_P is the irradiance angle of the inspected point P, $\alpha(h)$ is the decay rate along the central axis direction, $\beta(h \tan \theta)$ is the decay rate along the radius direction, $L(h, \sqrt{x^2+y^2})$ is the decay function of distance. Among them, I_C, $\alpha(h)$, $\beta(h \tan \theta)$, $L(h, \sqrt{x^2+y^2})$ are affected mainly by LED's lighting properties, and they can be confirmed by calibration experiments within the same batch of LEDs.

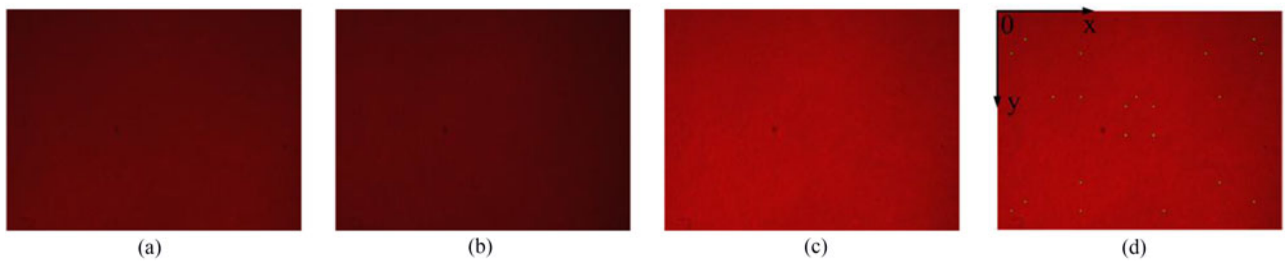


Fig. 3. LEDs irradiating results analysis. (a) The irradiance of LED A, (b) The irradiance of LED B, (c) The superposition irradiance of LED A and B, (d) Gray values analysis based on random dots.

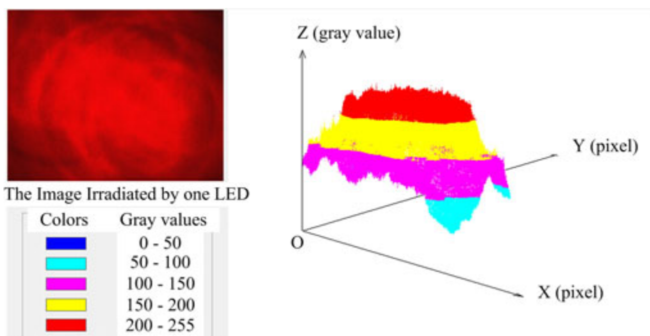


Fig. 4. The light intensity distribution of two LEDs superposition irradiating.

III. The Same Color Light Superposition Properties of LEDs

The vision illumination usually is composed by LEDs arrays. Experimental results [10]–[12] show that multi-LEDs irradiance properties are different from one LED irradiance. Therefore, researching its irradiance properties will be helpful to the design of LEDs arrays illumination. Following, setting two LEDs irradiating as an example to analyze and study their superposition properties of the same color for any specified point's brightness based on the single LED's irradiance model mentioned above. As shown in Fig. 3, two images are acquired based on the same field of view, which is irradiated by two different position LEDs respectively, and they have the same distance offsetting the center of the field of view. Fig. 3(a) is obtained under the irradiating of LED A and Fig. 3(b) is obtained under the irradiating of LED B. Fig. 3(c) is obtained under the irradiating of LED A and LED B. Especially, in order to simply the analysis process, in this manuscript, the light intensity of LED irradiating is evaluated by a gray value for any point of field of view. Following, within the same field of view, the gray values can be used to evaluate the dots' light intensity in the same condition. Certainly, before that, all gray values in the obtained images have be regulated to [0-255] by adjusting the camera aperture. Here, the gray value 100 is equal to 0.74uW per pixel area. Then, the irradiating result and their gray values distribution model are shown in Fig. 4. The labeled dots shown in Fig. 3(d) indicate the same positions in Fig. 3(a), (b) and (c), respectively. And they gray values will be analyzed and superimposed in order to study the same color light superposition properties of LEDs irradiance.

Based on the transformation relation between gray value and light intensity, gray values of labeled dots, whose positions are shown in Fig. 3(d), are obtained and shown in the left of Table I. Because LED A and LED B are fixed closely during experiment, their gray values are near too in the same positions. However, when these two LEDs both irradiate at the same time, their gray values in any dot are not equal to the sum gray value of LED A and LED B. It indicates that the light intensity is out of obeying the law of direct addition. On the base of analyzing the gray values in Fig. 3(c) and the addition sum gray values corresponding to the same dots in Fig. 3(a) and (b), it can be fitted as the following Equ.3 by least squares method:

$$z = 0.8967x + 0.9831y \tag{3}$$

where, x, y and z means the gray value in Fig. 3(a), (b) and (c) respectively.

Then, the gray value of any dot in Fig. 3(c) can be calculated by Equ. (3), and experimental results show that their gray value errors are less than 4.5% (as shown in the right column of Table I), which indicates that the light intensity superposition properties can be computed by Equ. (3) effectively when more than two LEDs irradiating at the same time.

IV. The LED Arrays Structure Illumination Design Method

In vision system, mono-color LEDs ring arrays structure illumination has evident symmetry in light intensity and it is beneficial to avoid the irradiance shadow to detected objects. Therefore, it is suitable for detecting irregular circular targets and small size targets, and it usually is used to detect surface scratches, printed characters, logos, barcode and other small size objects. As mentioned above, quality uniformity illuminations have great significance in improving visual inspection performances. Following, the design problem of mono-color LEDs ring arrays structure illumination will be analyzed and researched based on given parameters involving specially appointed engineering application.

The illumination structure is closely related to the detection requirements of field of views. Supposing the minimum radius of the detection field of view is r_v and the minimum distance of illumination to platform planed *XOY* is h_L. It asks to design a mono-color LED ring arrays structure illumination, in which the light intensity measured by gray values limited to $[c_1, c_2]$. If

TABLE I
LEDs Irradiating Results Analysis

Pixel coordinate			Gray values					
Dots	X	Y	Irradiated by LED A	Irradiated by LED B	Simultaneously irradiated by LED A and B	Gray values addition of LED A and B	Gray values obtained by fitted equation	Fitting Error
1	100	100	71	75	143	146	137.3982	–3.92%
2	924	100	75	60	121	135	126.2385	4.33%
3	100	668	90	85	164	175	164.2665	0.16%
4	924	668	93	62	143	155	144.3453	0.94%
5	462	334	85	83	156	168	157.8168	1.16%
6	562	334	89	84	165	173	162.3867	–1.58%
7	562	434	94	85	169	179	167.8533	–0.68%
8	462	434	93	86	165	179	167.9397	1.78%
9	300	300	86	80	153	166	155.7642	1.81%
10	300	600	95	85	171	180	168.7502	–1.32%
11	800	600	93	68	157	161	150.2439	–4.30%
12	800	300	86	67	143	153	142.9839	–0.01%
13	500	300	88	83	159	171	160.5069	0.95%
14	200	300	86	87	165	173	162.6459	–1.43%
15	600	700	102	83	173	185	173.0607	0.04%
16	300	700	101	89	176	190	178.0626	1.17%
17	300	150	79	79	146	158	148.5042	1.72%
18	950	150	74	57	121	131	122.3925	1.15%
19	750	150	83	68	142	151	141.2769	–0.51%
20	50	150	72	77	139	149	140.2611	0.91%
21	50	700	94	83	167	177	165.8871	–0.67%

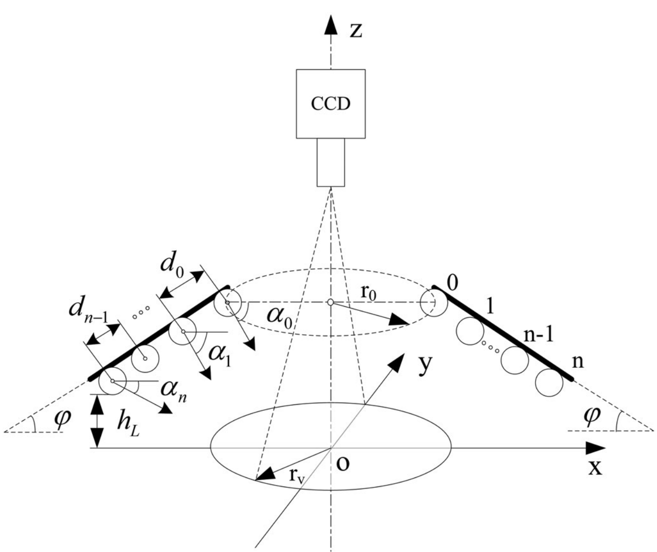


Fig. 5. The LEDs illumination model.

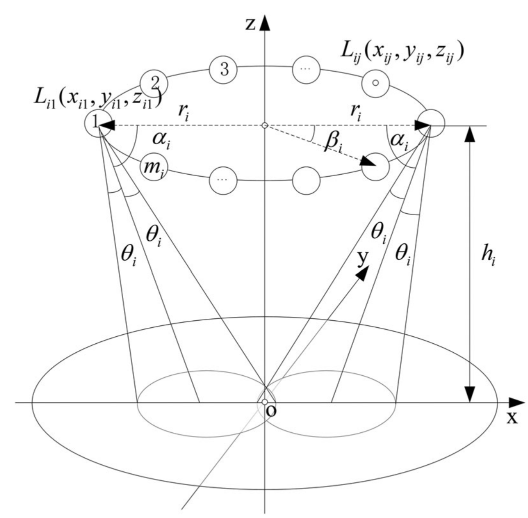


Fig. 6. The illumination model of single layer LEDs ring array.

c_1 and c_2 is the closer, it means that the light intensity is more uniform in the field of view.

Based on the given condition, the illumination model of LEDs arrays is built as shown in Fig. 5, where $0, 1, \ldots, \mathrm{n}$ means the layer number of LEDs ring arrays in the illumination, respectively, and the radius of each LEDs ring array is r_i and its incident angle is α_i respectively, $i = 0, 1, \ldots, \mathrm{n}$. The angle of the center axial section *XOZ* and the view plane is defined as ϕ, and in the axial section direction, the distance between the *n-1*th layer LEDs array and the *n*th layer array is d_i, $i = 0, 1, \ldots, \mathrm{n}$. With the help of the built model, the illumination design problem will be transformed to an optimization design equations. That is to say, in this optimization design equations, it needs to confirm these parameters of n, r_i, α_i, ϕ and d_i in order to ensure the light intensity within the field of view $V = \{x^2 + y^2 \le {r_v}^2\}$ limited to $[c_1, c_2]$ and obtain the most light intensity uniformity.

Based on the analysis mentioned above, the optimization design equations can be expressed as following.

$$S = \min \left(\sum_{y=-\sqrt{{r_v}^2 - x^2}}^{\sqrt{{r_v}^2 - x^2}} \sum_{x=-r_v}^{r_v} \left(I_{P(x,y)} - \overline{u} \right) \right) \tag{4}$$

Subject to

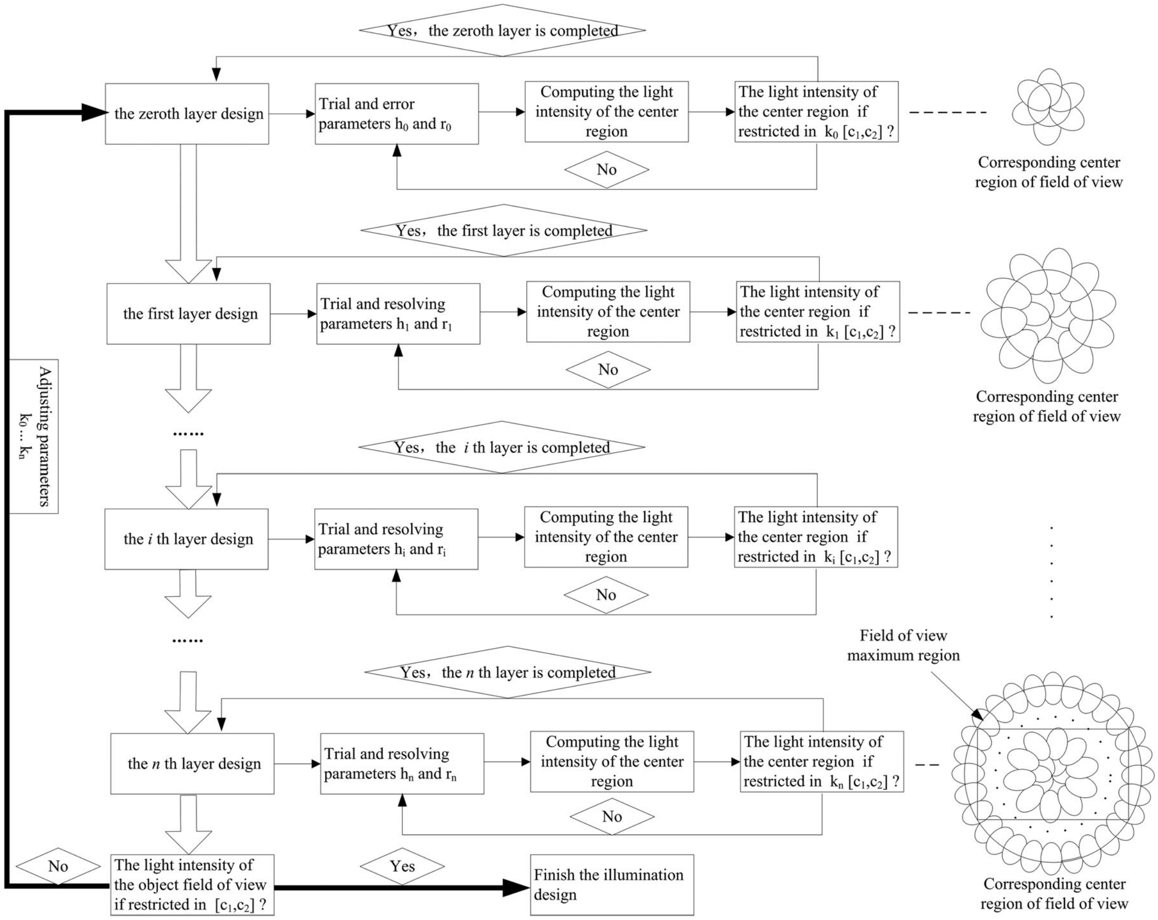


Fig. 7. The illumination design process of multi-layers LEDs ring arrays.

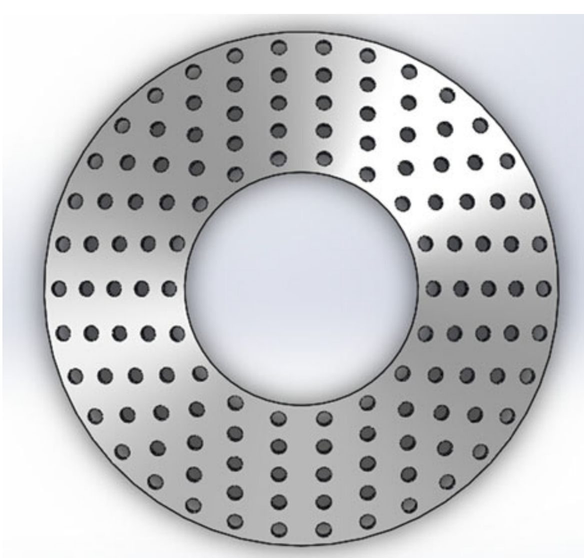


Fig. 8. The structure illumination of LEDs ring arrays.

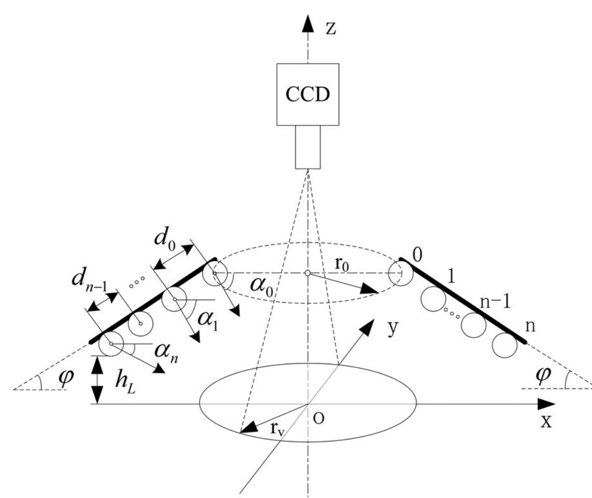


Fig. 9. The design parameters of illumination.

$$I_{P(x,y)} = \sum_{i=0}^{n}\sum_{j=1}^{m_i} I_{C_{i,j}} \cdot L(h_i, \sqrt{x^2+y^2}) \cdot \alpha(h_i) \cdot \beta(h_i \tan\theta_{P(i,j)}) \tag{5}$$

$$\overline{u} = \sum_{y=-\sqrt{r_v{}^2-x^2}}^{\sqrt{r_v{}^2-x^2}} \sum_{x=-r_v}^{r_v} I_{P(x,y)}/\pi \cdot r_v{}^2 \tag{6}$$

$$I_{P(x,y)} \in [255c - t, 255c + t] \tag{7}$$

$$P(x,y) \in \{x^2 + y^2 \leq r_v{}^2\} \tag{8}$$

TABLE II
SIZE PARAMETERS OF THE LEDs RING ARRAYS ILLUMINATION (1)

Technological parameters		The distance between the adjacent layer LEDs arrays	
r_v	12.73	d_0	6
h_L	15	d_1	6
r_o	27	d_2	6
φ	23°	d_3	6

where $I_{P(x,y)}$ means the light intensity of the any point $P(x,y)$. The position of point $P(x,y)$ is limited to the field of view, i.e. $P(x,y) \in \{x^2 + y^2 \le {r_v}^2\}$. $I_{P(x,y)}$ is limited to $[255c - t, 255c + t]$ corresponding to $[c_1, c_2]$, where the c is the proportional coefficient of light intensity and gray value, and $2t$ is equal to the corresponding to the gray value $c_2 - c_1$. $\theta_{P(i,j)}$ means the incident angle of the j *th* LED in the i *th* ring LEDs array in the illumination to the point $P(x,y)$, $i = 0, 1 \cdots n$, $j = 0, 1 \cdots m_i$, and $m_i = [\frac{2\pi}{\beta_i}]$([] means the integral function). As shown in Fig. 6, β_i means the angle between two adjacent LEDs in the i *th* ring LEDs array in the illumination, and r_i is the radius of the i *th* ring LEDs array in the illumination. Consequently, the angle of the center axial section *XOZ* and the view plane φ can be defined as following.

$$\varphi = atc\tan\frac{h_0 - h_n}{r_n - r_0} = atc\tan\frac{z_0 - z_n}{r_n - r_0} \quad (9)$$

$$h_0 - h_n \ge h_L \quad (10)$$

where h_0 means the vertical distance from the zeroth layer of the LEDs array in the illumination to the platform. z_0 and z_n is the *Z* axis value of the *zeroth* layer and the *n*th LED arrays, respectively.

Analyzing the design Equ. (4)–(10), we know that it needs a large amount of calculation and it is time-consuming, of course, which depends on the size of the field of view. It can be converted to the following the proposed method of hierarchical design to simplify the design process and reduce the calculation difficulty. In other words, it can be decomposed into two sub-problems, one is the illumination design problem of the single layer LEDs ring array, the other one is the illumination design problem of multi-layers LEDs ring arrays..

A. The Illumination Design Problem of the Single Layer LEDs Ring Arrays

As for the problem of the single layer LEDs ring array illumination, especially for the problem of the top layer LEDs ring array illumination, as shown in Fig. 6, it firstly can confirm the detected height h_i and the radius r_i of the ring structure illumination based on the technological conditions, and consequently it will simplify the illumination design Equ. 4∼10. Then, it is easy to confirm the angle β_i and α_i according to the light intensity requirement in the field of view. Finally, the design of the single layer LEDs ring array illumination is finished.

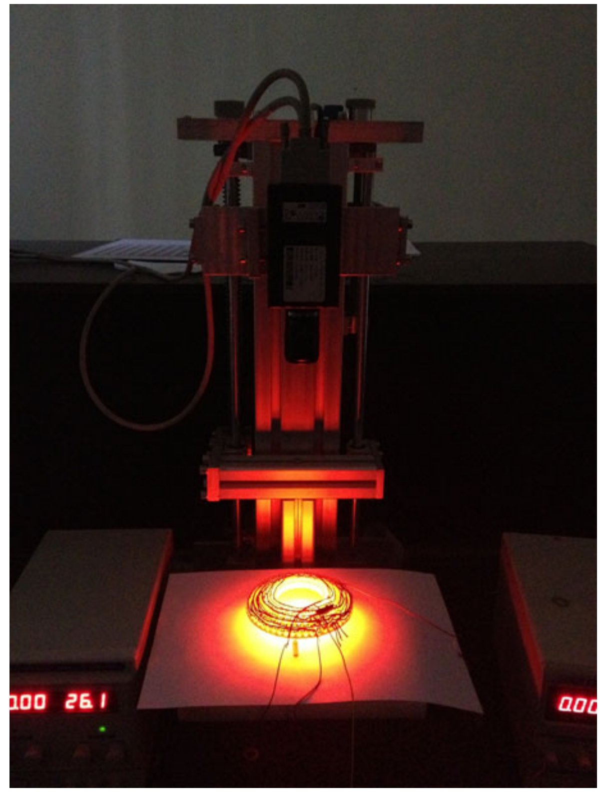


Fig. 10. The illumination experiment.

Fig. 11. The acquired image.

B. The Illumination Design Problem of Multi-Layers LEDs Ring Arrays

Based on the designed single layer LEDs ring array illumination, it can match multi-layers LEDs ring arrays illumination according to the design process shown in Fig. 7, and eventually obtain the multi-layers LEDs ring arrays illumination. Where $0 < k_0 < k_1 < \cdots < k_i < \ldots < k_n \le 1$, $k_0, k_1, \cdots, k_i, \ldots, k_n \subseteq (0,1)$, and they are impacted by each layer LEDs light superposition. The design process can be controlled by switching each layer LEDs light in turn, and then the

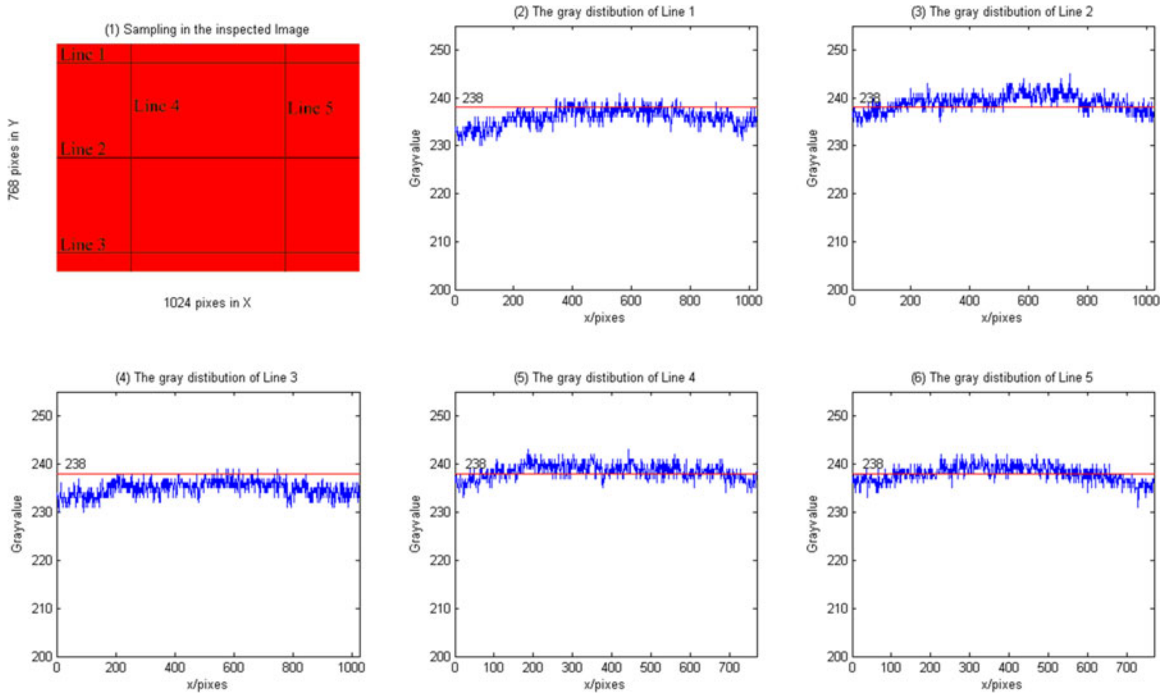


Fig. 12. The uniformity analysis.

value of k_i is determined by measuring the light intensity in the field of view.

V. Experimental Results and Analysis

In the micro-devices inspection system, it usually uses the structure illumination of LEDs ring arrays in order to highlight the detected object in all direction. In this experiment, the structure illumination design problem of mono-color multilayer LEDs ring arrays is illustrated by the proposed method, which considering the PCB solder joint inspection as the application background. Based on the technological conditions of vision inspection system, the minimum height from the illumination to PCB is 15 mm, which ensures the safe operation of inspection system. Using the JAI CV-M9CL camera, a 3CCD camera, 24 bits RGB, the wavelength of red light between 600 nm to 650 nm, 300 mm object distance, 18 mm $\times$ 12 mm detected field of view, and using smooth white paper as the calibration board during the experimental process. As shown in Figs. 8 and 9, we designed the mono-color (red) five layers LEDs ring arrays structure illumination based on the proposed design method. Its size parameters are shown as Table II and Table III, where the computed field of view is 18 mm $\times$ 18 mm.

In order to test the irradiance uniformity, as shown in Fig. 10, the designed LEDs illumination was fixed in the testing platform developed by us. By adjusting the aperture, the brightness of images captured by JAI CV-M9CL camera was controlled in gray values less than 255. The captured image is shown in Fig. 11, whose pixels size is 1024 $\times$ 768. Following, the uniformity of the captured image will be analyzed and the uniformity is evaluated by their gray values in order to evaluate the rationality of the designed illumination.

TABLE III
Size Parameters of the LEDs Ring Arrays Illumination (2)

Irradiating angle		Distribution angle within the same LEDs layer	
α_0	47.5	β_0	20
α_1	42.0	β_1	16.3636
α_2	36.6	β_2	13.8461
α_3	31.0	β_3	12
α_4	22.9	β_4	10.5882

As shown in Fig. 12(1), gray values distributed in five lines were analyzed, and results were shown in Fig. 12(2–6). These results reveal that, (1) the central image's uniformity is better than the part of the edge, and the light intensity is slightly higher than the edge too; (2) gray values fluctuate between 229$\sim$245 in the scope of the entire field of views; and compared with the expected gray value 238, the upper deviation is 2.94%, the lower deviation is 3.78%; (3) gray values of adjacent points are not smooth in each detected line, which roots in the calibration plate surface roughness. In addition, illumination and calibration board parallelism, imaging axis and calibration board verticality also affect the measurement of gray values. Experimental results show that the light intensity fluctuation is less than 3.78% by the proposed illumination design method, which indicates the light intensity uniformity within the field of view is good. Meanwhile, experimental results also show the light intensity fluctuation range is related to the calibration board. In this experiment, the smooth white paper used as the calibration board also affects the light intensity to some extent, if using a better calibration board, it can obtain a better light intensity uniformity.

VI. Conclusion

A structure illumination design method of LEDs arrays is proposed in this paper. Firstly, the single LED irradiating model is built based on analyzing its irradiance properties, which is used to derive the illumination model. Secondly, the model of multi-LEDs superposition irradiating is built, and experimental results indicate that the light intensity can be computed by a fitted linear equation effectively when more than two LEDs irradiating at the same time. Thirdly, it analyzes the structure illumination design method of LEDs ring arrays, and proposes the design model of uniformity illumination. On basis of this model, the illumination design method is decomposed into two sub-problems to simplify the design process, which reduces the design difficulty. Experimental results show that the light intensity deviation is less than 3.78% by the proposed illumination design method. Experimental results also show that, if using a better calibration board, it can obtain a better light intensity uniformity. The further work would be to study the structure illumination design problem of multi-color LEDs arrays.

Acknowledgment

The authors would like to thank Corporation OPT Machine Vision, China, for providing with experimental facilities and testing assistance.

References

[1] A. W. M. Smeulder *et al.*, "Visual tracking: An experimental survey," *IEEE Trans. Pattern Anal.*, vol. 36, no. 7, pp. 1442–1468, Jul. 2014.

[2] A. Giaquinto, G. Fornarelli, G. Brunetti, and G. Acciani, "A neurofuzzy method for the evaluation of soldering global quality index," *IEEE Trans. Ind. Informat.*, vol. 5, no. 3, pp. 56–66, Sep. 2009.

[3] Z. M. Zhu, H. Liu, and S. M. Chen, "The design of diffuse reflective free-form surface for indirect illumination with high efficiency and uniformity," *IEEE Phonics J.*, vol. 7, no. 3, Jun. 2015, Art. no. 1633510.

[4] H. W. Xie, X. M. Zhang, Y. C. Kuang, and G. Ouyang, "Solder joint inspection method for chip component using improved adaboost and decision tree," *IEEE Trans. Compon. Packag. Manuf. Technol.*, vol. 1, no. 12, pp. 2018–2027, Dec. 2011.

[5] N. S. S. Mar, P. K. D. V. Yarlagadda, and C. Fookes, "Design and development of automatic visual inspection system for PCB manufacturing," *Robot. Cim-Int. Manuf.*, vol. 27, no. 10, pp. 949–962, Oct. 2011.

[6] F. P. Wu and X. M. Zhang, "An inspection and classification method for chip solder joints using color grads and Boolean rules," *Robot. Cim-Int. Manuf.*, vol. 30, no. 5, pp. 517–526, May 2014.

[7] F. P. Wu and X. M. Zhang, "Feature-extraction- based inspection algorithm for IC solder joints," *IEEE Trans. Compon. Packag. Manuf.*, vol. 1, no. 5, pp. 689–694, May 2011.

[8] J. Jiang, J. Cheng, and D. Tao, "Color biological features-based solder paste defects detection and classification on printed circuit boards," *IEEE Trans. Compon. Packag. Manuf.*, vol. 2, no. 5, pp. 1536–1544, May 2012.

[9] Z. M. Zhu, X. H. Qu, G. X. Jia, and J. F. Ouyang, "Uniform illumination design by configuration of LED arrayand diffuse reflection surface for color vision application," *J. Display Technol.*, vol. 7, no. 2, pp. 84–89, Feb. 2011.

[10] Z. M. Zhu, X. L. Jin, H. Yang, and L. S. Zhong, "Design of diffuse reflection freeform surface for uniform illumination," *J. Display Technol.*, vol. 10, no. 1, pp. 7–12, Jan. 2014.

[11] Z. M. Zhu, H. Liu, and S. M. Chen, "The design of diffuse reflective free-form surface for indirect illumination with high efficiency and uniformity," *IEEE Photon. J.*, vol. 7, no. 3, Jun. 2015, Art. no. 1600510.

[12] H. Yang, J. W. M. Bergmans, T. C. W. Schenk, J. P. M. G. Linnartz, and R. Rietman, "Uniform illumination rendering using an array of LEDs: A signal processing perspective," *IEEE Trans. Signal Process.*, vol. 57, no. 3, pp. 1044–1057, Mar. 2009.

[13] I. Moreno, M. Avendano-Alejo, and R. I. Tzonchev, "Designing light-emitting diode arrays for uniform near-field irradiance," *Appl. Opt.*, vol. 40, no. 10, pp. 2265–2272, Oct. 2006.

[14] A. J. W. Whang, Y. Y. Chen, and Y. T. Teng, "Designing uniform illumination systems by surface-tailored lens and configurations of LED arrays," *J. Display Technol.*, vol. 5, no. 3, pp. 94–103, Mar. 2009.

[15] J. Liu *et al.*, "Impact of detector spatial uniformity on the measurement of averaged LED intensity," *IEEE Photon. J.*, vol. 6, no. 1, Feb. 2014, Art. no. 6800107.

[16] C. Chen and C. Tsou, "Silicon-based white LED packaging module with an integrated RGB color sensor," *IEEE Photon. Technol. Lett.*, vol. 27, no. 5, pp. 553–556, Mar. 2015.

[17] S. K. Ng, K. H. Loo, Y. M. Lai, and C. K. Tse, "Color control system for RGB LED with application to light sources suffering from prolonged aging," *IEEE Trans. Ind. Electron.*, vol. 61, no. 4, pp. 17788–1798, Apr. 2014.

[18] K. Modepalli and L. Parsa, "Dual-purpose offline LED driver for illumination and visible light communication," *IEEE Trans. Ind. Appl.*, vol. 51, no. 1, pp. 406–419, Jun. 2015.

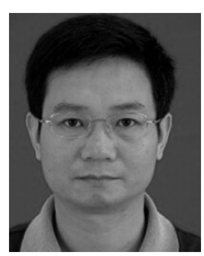
[19] Y. C. Fang, Y. F. Tzeng, and K. Y. Wu, "A study of integrated optical design and optimization for LED backlight module with prism patterns," *J. Display Technol.*, vol. 10, no. 10, pp. 840–846, Oct. 2015.

[20] A. Phandharipande and D. Caicedo, "Adaptive illumination rendering in LED lighting systems," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 43, no. 5, pp. 1052–1062, Sep. 2013.

[21] A. Kumar, F. Tung, A. Wong, and D. A. Clausi, "A decoupled approach to illumination-robust optical flow estimation," *IEEE Trans. Image Process.*, vol. 22, no. 10, pp. 4136–4147, Oct. 2013.

Fupei Wu was born in 1980. He received the Ph.D. degree in mechanical engineering from South China University of Technology, Guangzhou, China, in 2009.

He is currently working in the Department of Mechatronic Engineering as an Assistant Professor, Shantou University, Shantou, China. His main research interests include machine vision, particularly in automated optical inspection systems and adaptive image recognition.

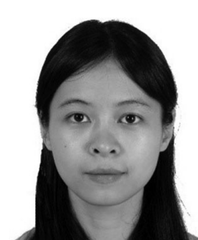


Shengping Li received the M.S. degree in control theory and control engineering from Beijing Institute of Technology, Beijing, China, in 1992, and the Ph.D. degree in control theorem and control engineering from Huazhong University of Science and Technology, Wuhan, China, in 1995.

He is currently a Professor in the Department of Mechatronics Engineering, Shantou University, Shantou, China and serves as the Vice Dean of the College of Engineering at Shantou University. His current research interests include robust control, adaptive control, robust design of mechanical product, intelligent control theory and applications.

Xianmin Zhang was born in 1964. He received the Ph.D. degree from Beijing University of Aeronautics and Astronautics, Beijing, China, in 1993.

He worked in South China University of Technology as a Professor, since 2003, and was the Dean of College of Mechanical and Automotive Engineering, South China University of Technology, in 2013. His research interests include precision mechanism design and dynamics, as well as inspection technique.



Weilin Ye received the M.S. and Ph.D. degrees from the College of Electronic Science and Engineering, Jilin University, Changchun, China, in 2009 and 2012, respectively.

She is currently a Lecturer in the College of Engineering, Shantou University, Shantou, China, and engages in design and fabrication of infrared sensors.