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A contour calculation method for rapid freeform reflector construction with ellipsoid patches

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ABSTRACT

This paper presents a contour calculation method (CCM) for the freeform reflector design. Conservation of energy relates the light flux from a Lambertian-type point source to a desired irradiance and a discrete spot distribution on a target plane. This relationship determines the edges of the reflector patches, thus, enabling the design of a non-imaging freeform reflector based on a series of ellipsoid patches modeled as NURBS curves in Rhinoceros. As an example, we present a freeform reflector design composed of 6400 ellipsoid patches to illuminate a surface with 94% uniformity. A computer calculation takes 18.5 s.

1. Introduction

As a third-generation semiconductor lighting source, the light emitting diode (LED) has lots of advantages, such as high illumination efficiency, full color, low energy consumption, fast reaction, long lifespan, friendly to environment, easily motivated [1,2], which can be widely used in traffic signal, projection display, general illumination and automotive lighting as well [3–5].

The freeform optical components are considered the best technique to get the prescribed irradiance. In recent years, there are many kinds of design methods for freeform optical component in non-imaging optics, such as the Tailored Freeform Surface Method [6,7] and the Simultaneous Multiple Surfaces (SMS) Method [8,9]. Based on equi-flux regions between the intensity of the source and the target illumination, Ding and Wang applied a tailoring method to solve partial differential equations (PDE) and generated faceted reflectors [10,11]. For the design of smooth freeform reflector surface various iterative optimization procedures were used [12–14]. However, the problems on lower degrees of freedom and non-efficiency of the iterative procedure make them difficult to be used by optical designers. Based on the imaging property of ellipses, Oliker presented a method to design freeform reflector by using ellipsoid patches [15]. In order to obtain a smooth reflector surface, he used hundreds of ellipsoids to establish smooth reflector, but it was apparently time consuming and non-effective. By using Oliker algorithm, Fournier used surface integrability condition to obtain a smooth freeform reflector [17–19]. The method made possible generation of desired irradiance distributions. However, Source-target mapping method for design reflector may even depend on the accuracy of interpolate scheme.

In this paper, with a formulation based on contour calculation method (CCM), we present a flexible algorithm approximating a solution to the general problem of prescribed illumination tailoring with freeform reflector surface and a Lambertian-type point source emitter. We used this method to design an on-axis illumination pattern. The irradiance uniformity of the freeform reflector is evaluated for the illumination pattern, and the optical characteristics of the freeform reflectors are analyzed. The computation time with CCM is faster than the method proposed by Fournier. Besides, our method is completely different from prior approaches, and consequently has distinct advantages, notably the freedom to design arbitrary forms of illumination in a few seconds.

The rest of this paper is organized as follows. Section 2 introduce the theory of the construction method. The design methods of freeform reflector surface, the analysis of the on-axis reflectors are made in Section 3. Conclusions are summarized in Section 4.

2. Contour calculation method (CCM)

2.1. Establishment of source-spot maps

As shown in the vector form in Fig. 1, the light source with intensity $I_{(\mathbf{m})}$ is assumed to be positioned at the origin O in the Cartesian coordinate system. We assume that $\mathbf{r}$ is the vector of the incident light at point P and it passes through input region Ω. From

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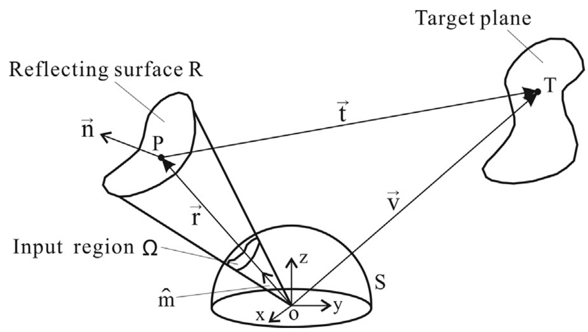

Fig. 1. The freeform reflector system in vector formulation.

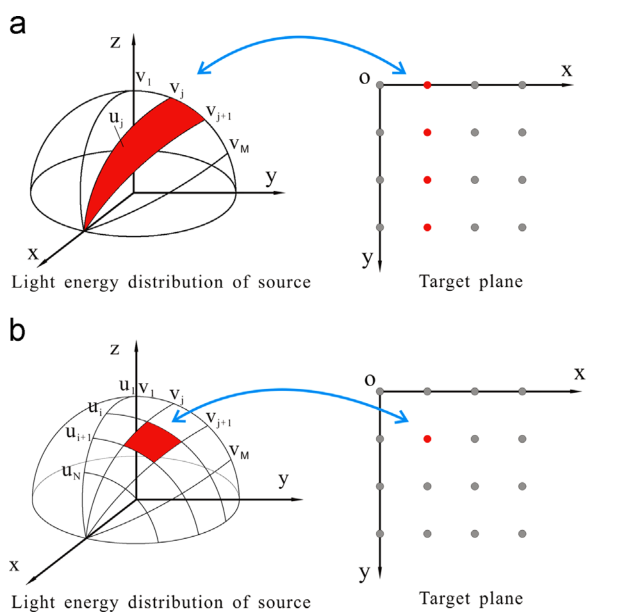

Fig. 2. Schematic of light flux mapping between source and target plane. (a). Slicing of the source intensity and target plane on the v direction. (b). Slicing of the source intensity and target plane on the v and u directions at the same time.

Fig. 1, **r** can be expressed as:

$$\mathbf{r}_{(\mathbf{m})} = \rho \times \mathbf{m} \tag{1}$$

where $\mathbf{m}$ ($\mathbf{m} \in \Omega$) denotes the unit vector of the incident ray. While **t** is the vector of reflective light by the freeform reflector from point P to point T. According to the law of reflection, the relationship between the unit vector $\mathbf{m}$ of the incident ray and the unit vector **t** of the reflected ray at point P can be written as [15,16]:

$$\mathbf{t} = \mathbf{m} - 2 \times (\mathbf{m} \times \mathbf{n}) \times \mathbf{n} \tag{2}$$

where, n is the unit normal of reflector surface R at point P.

With square or rectangular illumination distribution, the source and target plane has mirror symmetry. Thus, only first quadrant of the reflector needs to be constructed and mirror operation is implemented to establish the whole reflector. As shown in Fig. 2, spherical coordinates (u,v) and Cartesian coordinate (x,y) are employed to denote the intensity distribution of the light source and desired irradiance distribution on the target plane, respectively [11]. Here, u is the angle between the incident ray and the z axis, and v is the angle between the incident ray and the z axis. Each of the (x,y) coordinates stands for the pixel on the target plane. The first quadrant intensity distribution of source Ω is divided into $M \times N$ parts with equal flux. M and N are employed to denote the v and u directions, respectively, which are also the number of pixels on the target plane at the same time. If there is no reflection and scattering loss, the flux received will be equal to the source flux. This energy conservation law can be expressed as [15,16]:

$$\iint_R I_{(u,v)} \times d\Omega = \sum_{i=1,j=1}^{M,N} L(\mathbf{V}_{i,j}) \tag{3}$$

where, $d\Omega = \cos(u) \times du \times dv$, $I(u,v)$ is the radiant intensity in (u,v) direction of a source, R is the area of the freeform reflector surface, $L(\mathbf{V}_{i,j})$ equals the output flux received by $\mathbf{V}_{i,j}$ on the target screen. $\mathbf{V}_{i,j}$ represents the unit position vector of point T, and i ($i=1,\ldots,N-1,N$) and j ($j=1,\ldots,M-1,M$) are the indices of the grid along u and v directions, respectively.

According to the variables separation method, the energy conservation on the v direction can be obtained with Eq. (4), and u_{ej} represents the sum of light intensity between v_i and v_{i+1}, which are mapped into the pixels of target plane as shown in Fig. 2(a). Furthermore, Eq. (5) may be derived from Eq. (3), as shown in Fig. 2(b):

$$\int_{v_j}^{v_{j+1}} \int_0^{u_{ej}} I_0 \times \cos^2(u) \times \cos(v) \times du \times dv = \sum_{i=1}^{M} L_{ij} \tag{4}$$

$$\int_{v_j}^{v_{j+1}} \int_{u_{i,j}}^{u_{i+1,j}} I_0 \times \cos(v) \times \cos^2(u) \times du \times dv = \frac{\sum_{i=1}^{M} L_{ij}}{N} \tag{5}$$

where I_0 is the central light flux of the Lambertian-type source.

Then integral Eq. (4) and Eq. (5), the spherical coordinates (u,v) can be expressed as Eq. (6) and Eq. (7), respectively:

$$v_{j+1} = \arcsin\left\{ \frac{4 \times \sum_{i=1}^{M} L_{ij}}{I_0[2 \times u_{ej} + \sin(2 \times u_{ej})]} + \sin(v_j) \right\} \tag{6}$$

$$2 \times u_{i+1,j} + \sin(2 \times u_{i+1,j}) = \frac{4 \times \sum_{i=1}^{M} L_{ij}}{N \times I_0 \times [\sin(v_{j+1}) - \sin(v_j)]} + 2 \times u_{ij} + \sin(2 \times u_{ij}) \tag{7}$$

Based on geometrical relation, u_{ej} is defined in Eq. (8):

$$u_{ej} = \arcsin\left[\sqrt{\sin^2(\varphi_{max}) - \tan^2(v_j) \times \cos^2(\varphi_{max})} \right] \tag{8}$$

where, φ_{max} is the maximum collection angle of the freeform reflector. Taking $v_1 = 0$, $u_{1,j} = 0$ as the initial value condition, Eq. (6) and Eq. (7) can be solved respectively by the fourth-order Runge–Kutta method and the Bisection method [20].

2.2. Construction of the reflector

In this section, the construction of the freeform reflector surface from patches of ellipsoid will be discussed. Supporting ellipsoid method was proposed by Oliker, and discrete target distribution on the target was obtained by using a finite ellipsoids. The freeform reflector surface is constructed from a series of ellipsoids surface which have the common focus at the origin of O and another focus at the pre-described target plane [15,16], as shown in Fig. 3.

In the previous subsection, we have defined a finite set of pixels $M \times N$ on the target plane. To obtain uniform illumination, the right hand side of the energy balance in Eq. (3) should be expressed in this case as the patch ellipsoid energy:

$$L_1 = L_2 = \cdots = L_{M \times N-1} = L_{M \times N} \tag{9}$$

Therefore, for each patch of ellipsoids, the energy conservation equation of Eq. (3) can be expressed as follows:

$$\iint_{A_k} I_{(\mathbf{m})} \times d\Omega_{(\mathbf{m})} = L_k, \quad (k = 1, \ldots M \times N) \tag{10}$$

where, $I_{(\mathbf{m})}$ is the radiant intensity in $\mathbf{m}$ direction of the source, Ω is the solid angle of the source, A_k is the region of a patch of