Efficient freeform optics for street lighting applications

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The recent developments of our method to design two freeform optical surfaces (either refractive or reflective) using an optimized ray mapping computation are presented. The procedure is based on the Monge-Kantorovich theory of optimal mass transport, and the related conditions for an optimal mapping. The procedure is illustrated by designing an efficient street lighting lens, achieving an optical efficiency over 92% while at the same time producing a prescribed luminance pattern on the road.

1 Introduction

The recent developments in LED technology have created an attractive light source for new efficient illumination systems. However, their high luminous efficacy can only be fully exploited in combination with highly efficient optics, allowing to tailor the light into a given target irradiance.

The design of freeform optics is now the privileged route to tackle this challenge [1-2]: using relatively few optical components, a complex non-radially symmetric irradiance pattern can be achieved. Combining these capabilities with a high optical efficiency brings up new problems and leads to sensitive numerical schemes.

The first section will present the setup of the problem targeted in this application. The second shows how two freeform optical surfaces can be computed using an optimized ray mapping computation. Finally the last section illustrates the procedure with the design of an efficient street lighting lens, achieving an optical efficiency of 92%, and shows the corresponding light distribution.

2 Overview

The geometry of the problem is shown in Fig. 1:

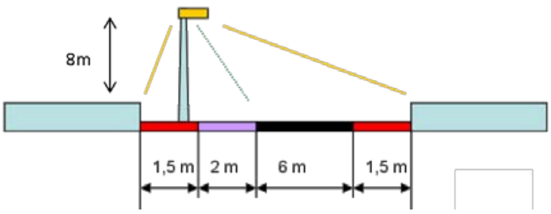

Fig. 1 *Geometry of the problem*

The light source and the secondary optic are positioned 8m high above the ground, and the street dimensions are approximately 11x50m. The secondary optic should achieve the prescribed light intensity distribution shown in Fig. 2 (angular light distribution, extracted from the measurement of another system, hence the asymmetric shape comes) whilst at the same time maximizing the optical efficiency.

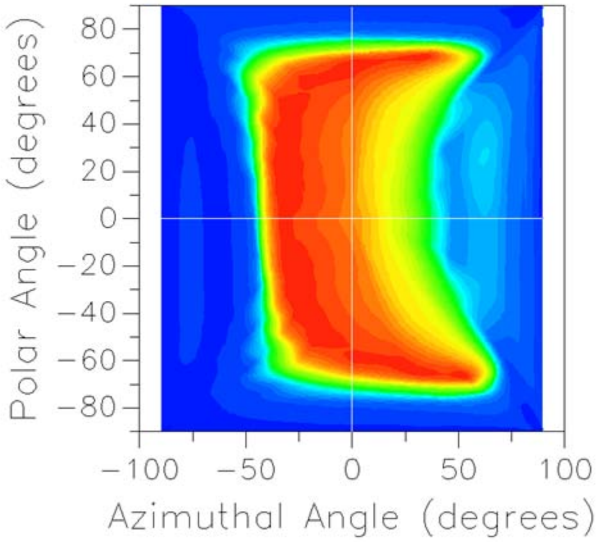

Fig. 2 *Prescribed light intensity distribution, extracted from the measurement of another lighting system.*

3 Design procedure

A two stage design process is used [3] : first a ray mapping is computed, indicating for each ray coming out of the source where it has to go on the target, so that the prescribed light distribution is achieved.

Computing this light path boils down to finding a mapping between two planar projection of 1) the light source intensity distribution, and 2) the prescribed target distribution. In mathematical terms, one is looking for a mapping turning one density into the other.

This problem does not have a unique solution, and in the present case the difficulty comes from the optical design constraints: the mapping must be computed in such a way that it is compatible with the actual reconstruction of a smooth (mathematically C^1) surface. This is termed the integrability condition, and expressed as:

$$\mathbf{N} \cdot (\nabla \times \mathbf{N}) = 0 \qquad (1)$$

where **N** represents the field of normal vectors to the surface [4].

The procedure from Haker [5] is used to approximate this condition and is shown in this application to lead to acceptable results. Haker derived a first-order parameter-free procedure, allowing reduction of the curl of a mapping between two densities. Although we do not give a formal proof, removing the mapping's curl also leads to better compatibility with the integrability conditions, probably because of the implicit connection between the mapping's curl and the normal vector field's curl.

In a second stage, the optical surfaces themselves are reconstructed using a standard least-squares procedure. Starting from a triangle mesh representing a half-sphere, the vertex positions of the triangulation are optimized, such that the source rays (deflected at each mesh face – i.e. when intersecting a triangular face) are directed towards the target points given by the mapping.

4 Virtual prototype and simulation results

Using the procedure outlined above, the following two freeform surfaces were designed (see Fig. 3). The simulation results are shown in Fig. 4 and are in good agreement with the prescribed distribution. The optical design was modeled assuming that the lens was made of PMMA and the resulting optical efficiency (including Fresnel losses) is around 92%. Capturing the full half space in the positive z direction from the source and having the ray normal incidence on both optical surfaces relatively low (typically below 10°) make this high efficiency possible, notably by limiting the Fresnel losses.

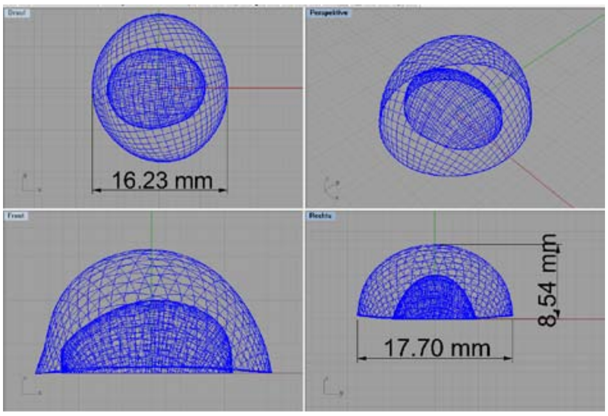

Fig. 3 *Designed freeform surfaces*

Using two freeform surfaces allows a reduction of Fresnel losses: the incidence angle on each of the surfaces is smaller than the angle one would see with just one freeform surface, and the losses are thus reduced.

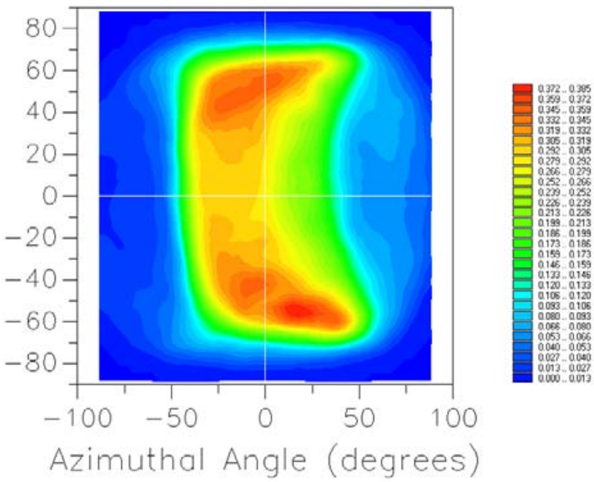

Fig. 4 *Simulation results*

5 Conclusion

This article presents a new design method for the construction of freeform surfaces using the computation and optimization of a ray mapping. The algorithm is quick (typically a few minutes for the design presented here on a standard desktop computer) and allows the design of both freeform surfaces of a lens.

The application of this procedure to a typical street lighting application shows that a very high optical efficiency can be reached (92% in this case) whilst at the same time controlling precisely the distribution of the light to adhere to a given prescribed intensity.

References

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