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Abstract: We introduce a class of pictorial irradiance patterns that freeform optics can render sharply despite the blurring effect of extended light sources; show how to solve for the freeform geometry; and demonstrate a fabricated lens.

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Freeform optics can be tailored to project an arbitrary irradiance density patterns, if one assumes sufficient propagation distances and a light source whose étendue is suitably close to zero. Experience teaches that light sources small enough for "picture-throwing" freeforms are often impractically dim, wasteful, hot, and difficult to package compactly. Extended light sources are considerably more practical, but result in unacceptably blurry irradiance patterns. Indeed, for almost all target patterns, no accurate freeform tailoring is possible, because almost all target patterns lie outside of the range of the blur convolution imposed by the extended light source. Perhaps uncoincidentally, the literature of extended-source freeforms (e.g., [1–5]) features highly flexible mathematical frameworks yet demonstrations are limited to achieving uniform illumination in a rectangular region, with blurred boundaries.

We suggest that this is overly pessimistic, as there are highly structured sharp-edged irradiance patterns that do lie within the range of the convolution: A target irradiance pattern can be realized from an extended light source iff the pattern can be decomposed into a positive superposition of 0-, 1-, and 2-dimensionally "smeared" images of the light source. The 0- (respectively, 1-) dimensional elements are fully (resp., partially) focused and therefore inherit the sharp boundaries of the light source.

To obtain and exploit this decomposition, we take a signal-processing approach and solve a spatially variant non-negative deconvolution problem, recognizing that the convolution operator (a.k.a. blur kernel) must vary across the (unknown) freeform surface. If such a deconvolution exists, it can be recovered (using eqn. (3) below) and used to compute the freeform geometry (using eqn. (2) below).

This presents a chicken-and-egg problem where the freeform surface and the deconvolved pattern are both unknown and depend on each other. We begin with a proxy surface estimated for a zero-étendue source, and note that both optimizations (deconvolution, surface estimation) can be given strictly convex formulations, consequently a strategy of alternating one optimization relative to the other will converge. Results are quite good after a single iteration, as demonstrated below.

1. Estimating zero-étendue freeform geometry from source and target densities

To calculate the freeform surface geometry, we use a simple fixpoint motivated from optimal mass transport theory: Let p be the height field of the optical surface and let $T \doteq r(p)$ be a field of transport vectors taking light rays from the optical surface to the projection surface according to the geometric law $r(\cdot)$ of reflection or refraction. Given a zero-étendue source, for any surface geometry p the transport T is completely known, thus we can propagate the source energy density forward to the optic, where we denote it f_0. If T is also 1-to-1, we can also propagate the target energy density (denoted f_1) backward. We do both, and compare them at the optical surface. There, the backpropagated density is

$$b_1 \doteq (f_1 \circ T^{-1}) \cdot \det(DT) \tag{1}$$

The first term carries the target densities back along the transport vectors T and the second term corrects them to account for local beam divergence in T. The surface heights are then adjusted according to the mismatch between the backward and forward densities, scaled the Jacobian of the transport generator $r(\cdot)$:

$$\Delta p \propto (b_1 - f_0)\,\frac{d\|T\|}{dp} \tag{2}$$

This can be justified as a temporal derivative of Kolmogorov's dual mass transport formulation, generalized for the nonlinearity of the transport generator. Detailed surface geometries, typically bicubic surfaces with $> 10^6$ control points, can be computed in seconds. The author has used this rule to design and fabricate hundreds of picture-forming lenses for art installations, with focal lengths ranging from 0.1Ø to 1000Ø (diameters).

2. Correction for extended light sources

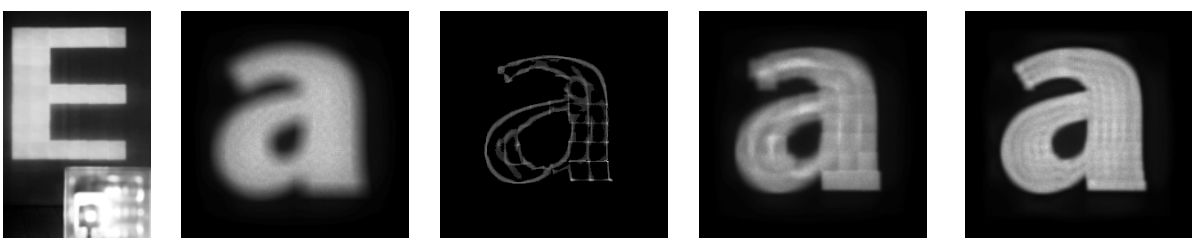
For deconvolution, we first estimate the local blur kernel at each point $\mathbf{x}$ on the optical surface by placing a virtual pinhole at that point and computing the projected image $h(\mathbf{x})$ of the light source. We can then deconvolve by solving the Tikhonov-regularized least-squares problem

$$d_1^* = \arg\min_{d_1 \geq 0} \|d_1 * h - f_1\|_2^2 + \lambda \|\nabla(d_1 * h)\|_W^2, \tag{3}$$

where d_1 is the deconvolved target image, $d_1 * h$ is a spatially varied convolution of $d_1$with positionally-dependent blur kernel h, f_1 is the target pattern, $0 < \lambda \ll 1$ is a regularization weight, and ∇ is the gradient operator. The regularization term favors solutions that are spatially smooth except in areas where the original target pattern has strong edges (this selectivity is encoded in diagonal matrix $W \succ 0$).

3. Demonstration with realizable and unrealizable (but approximable) targets

We optimized and fabricated a freeform lens of effective focal length ≈ 2Ø that projects the letter "E" when illuminated by a square Lambertian source of diameter 0.1Ø. A single iteration yielded a design that essentially "tiles" the "E" with focused images of the light source (figure 1(a)). To show what happens when the target is *not* realizable from the source, we optimized a lens to project the letter "a" (figure 1(b-e)). The optimized approximation packs in tiles and edge-aligned "smears" to maximize sharp edges where physically possible.



(a) corrected (b) uncorrected (c) deconvolution (d) approx. corrected (3) same, smaller light

Figure 1. (a) Photograph of an "E" sharply rendered by a corrected freeform lens when illuminated with a relatively large square extended light source (visible in reflection on the lens at bottom). (b) Simulation of an "a" projected by an uncorrected freeform lens with the same light source and distances. (c) Spatially variant (approximate) deconvolution of the original "a" target. Dots indicate tile centers. (d) Simulation with an (approximately) corrected lens; note artifacts on diagonals and interior. (e) Same process, with 1/2-size light source.

References

1. R. Wester, G. Müller, A. Völl, M. Berens, J. Stollenwerk, and P. Loosen, "Designing optical free-form surfaces for extended sources," Opt. Express **22**, A552–A560 (2014).
2. A. P. Hirst and J. Muschaweck, "Irradiance tailoring for extended sources in 3D by implicit integral equation solution," in "Proc. OSA Conf. Imaging and Applied Optics," (2015).
3. R. Wu, Z. Zheng, P. Benitez, and J. C. Miñano, "The Monge-Ampere equation design method and its application to beam shaping," in "Proc. OSA Conf. Imaging and Applied Optics 2015," (OSA, 2015).
4. F. R. Fournier, W. J. Cassarly, and J. P. Rolland, "Designing freeform reflectors for extended sources," in "Proc. SPIE Conf. Nonimaging Optics," , vol. 7423 (2009), vol. 7423.
5. T.-Y. Wang, J.-J. Chen, K.-L. Huang, and C.-C. Wang, "Freeform lens design using a complementary optimization method for uniform illumination with extended LED light sources," in "Proc. SPIE Conf. Optical Design and Testing," , vol. 9272 (2014), vol. 9272.