Method designs free-form optical devices

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The simultaneous multiple surfaces technique is a versatile solution that calculates the surfaces of complex lenses and reflectors for non-imaging applications.

The simultaneous multiple surfaces (SMS) method was developed to calculate the surfaces of increasingly complex optical devices in nonimaging applications where the goal is efficient light transfer from a source to a target. It is primarily concerned with the design of devices such as waveguides, reflectors, and lenses. The method calculates all the optical surfaces (top, bottom, internal) of the lens or reflector simultaneously, starting from an initial area which has been pre-defined. Details of the early development of the method have been presented elsewhere.1-6 In this article, we give examples of our successful design solutions using SMS and outline the procedure by which subsequent parts of a device or optical system are calculated so that they meet the requirements of the application.

The first applications of the SMS method were devoted to the problem of coupling two input sets of rays with two output sets of rays. The simplest design case is a lens that perfectly focuses two source points, P and P’, onto two image points, Q and Q’ (see Figure 1). Only when the distances PP’ and QQ’ approach zero does the lens tend to the aplanatic case (where the system is free of spherical aberrations and circular coma of all orders). The goal in the SMS method is to design a system that generates a sharp image over as broad a plane of incidence as possible (i.e., when the distances PP’ and QQ’ are not negligible).7 So while the aplanatic strategy is to improve the optical quality near the axis, the SMS strategy looks at improving image quality more evenly across the whole field. The result is that there is always a segment of design points such that the maximum spot size for any point in the field is smaller in the SMS case than the aplanatic one. In other words, the SMS case is better. For example, for a given maximum rms spot size (for instance 25a.u.), the SMS design will have a wider useful field (4.4 degrees versus 3.1 degrees) than the aplanatic case (see Figure 2).

Figure 1. An SMS construction. The entire lens (right) is calculated from an initial pre-defined portion of the lens (left). With the SMS method, both surfaces of the lens are calculated simultaneously. P, P’: source points for optical rays. Q, Q’: image points.

Figure 2. The spot size is zero at normal incidence (0 degrees) for the aplanatic design (red) but at ±3 degrees for a 3-degree SMS design (blue). When the design points are at an appropriate distance, the average image formation quality across the field is better. (4.4 and 3.1 degrees for SMS and aplanatic, respectively).

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Figure 3. (A) Examples of SMS lenses designed to sharply image two wavefront planes (normal to \(v_1\) and \(v_2\)) onto two points (\(A_1\) and \(A_2\)). Neither of these lenses has rotational symmetry. (B) Evolution of the calculated regions on one of the lenses in (A).

Most optical design methods are worked out in 2D. The resulting lens or reflector surfaces are generated using linear or rotational symmetry. However, in nonimaging optics, there are problems with translating 2D geometrical solutions into 3D surfaces. In particular, rotational concentrators cannot achieve maximum focus on spherical receivers. Linear concentrators have problems when the receiver is surrounded by an optically dense medium. We have extended the SMS method to true 3D geometry. In a simple example, the 3D SMS method can be used to design asymmetric lenses that sharply image two planar wavefronts normal to the vectors \(v_1\) and \(v_2\) onto two points, \(A_1\) and \(A_2\) (see Figure 3). Since a rotationally symmetric optical system with a finite number of surfaces cannot sharply image two off-axis points, none of these lenses could have been rotationally symmetric.

The method is not based on any approximation other than those of geometrical optics, which enables designs for both nonparaxial and paraxial rays. Adding more surfaces to an SMS design enables a sharp image formation of more points across the field. We previously described designs for imaging applications with up to four aspheric surfaces. The selection of the design points is critical to attaining a good overall image quality. In our first example of a successful SMS design solution, two aspheric mirrors dramatically decrease the throw distance of a conventional projector (see Figure 4). In this case, the design rays are highly non-paraxial.

Because it calculates all surfaces simultaneously, the SMS method enables the design of optical systems in which the surfaces have multiple functions. Examples include free-form Kohler integrators with embedded lenslets to enable functional integration into the system being enhanced (see Figure 5), and RXI condensers (the term ‘RXI’ refers to refraction, R, reflection, X, and internal reflection, I) in which one of the surfaces works as both a reflector and a lens (see Figure 6).

RXI condensers for LED light sources demonstrate the power of the SMS design procedure. Here, a dome enclosing the LED device is first designed to capture and redirect the edge-most rays emitted from the source, which otherwise might be lost. Edge-ray fans from each side of the emitting chip entering this dome are then traced through a set distance to define the periphery of the lens. The ray bundle is internally reflected onto the back surface of the lens where it is then reflected back to the top surface at the appropriate angle. Refraction of the light through the upper surface is taken into account to ensure that the rays optimally reach the target. With the initial conditions of the lens periphery established using the edge-rays, successive profile segments can be calculated until all the light in the output range of the LED is captured and redirected. Different versions of the lens can be calculated by redefining the target, the LED source, or the housing for the system.

Although the SMS method repeats a basic procedure to calculate an entire optical device, it is not an iterative method because the points of the optical surfaces are not approximate and the surfaces are calculated simultaneously. This enables us to use the SMS method to explore unknown sectors of optical design in both imaging and nonimaging. For instance, the method can

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Figure 5. Acrylic RXI for Kohler integration. Photo courtesy of Light Prescriptions Innovators.

Figure 6. A free-form RXI design. A quadrant has been cut away to show the internal configuration and the trajectories of some rays from the LED chip to the exit.

be used to design a two-mirror system to efficiently transport the light from a cylindrical surface to a rectangular target or to generate an image plane perpendicular to the object plane with transversal magnifications having different signs (see Figure 7).

In future, we will look at fine tuning the method with computer optimization techniques to cement SMS as the method of choice for free-form optical design.13

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Figure 7. Two free-form mirror systems designed to (a) transport the light from a cylindrical source to a rectangular target and (b) to image an object onto a perpendicular target plane. SOE: secondary optical element.

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