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Review Article

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Reflectors in lighting design

Reflector-based non-imaging optics for lighting applications

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Abstract: Reflectors and lenses are common optical components used for image formation and the creation of beam patterns and light distributions. While lenses dominate imaging optics in many applications such as cameras and microscopes, reflectors are widely used in lighting and illumination optics. This article presents an overview of reflectors, including common reflector materials, modern design approaches, and applications. This article does not include information about physical and mathematical properties of reflectors; this information is thoroughly covered in optics industry and academic publications. There will be archetypes and examples discussed in the various sections of this article – neither is there any claim for completeness nor are these meant to be absolute. The intention of this article was to draw a comprehensive horizon around reflector applications and most of all their designs for lighting applications.

Keywords: free form; illumination; lighting; optical design; reflector.

1 Fundamentals and history

While mirrors have been used to view images for over 2000 years, optical reflectors are a more recent development. The use of flat and smooth reflecting surfaces as mirrors – beginning maybe with a calm water surface and evolving into polished metal pieces and modern metal-coated glasses – has a long tradition in human craftsmanship. At the ancient Olympic games, the Olympic fire was ignited with a parabolic mirror focusing sunlight onto a torch – a tradition preserved today. While Ptolemy's *Optics* from about 400 AD discussed the principles of geometric optics including reflectors, it was not until the Renaissance that reflectors were used in optical systems. In the middle of the 17th century, Gregory, Newton, and their contemporaries were thinking of and working on reflector-based telescopes for astronomical applications. While the reflectors shared imaging properties of mirrors, they were not flat; rather, they were spherical or parabolic to create image magnification. A variety of telescopes based on one or two reflectors resulted from this era. Their principles and designs are successfully used to this day.

Other fields of imaging optics are dominated by lens design, based on today's sophisticated quality of glass works and technical plastics. In lighting applications, the use of metal reflectors to collimate light dates back to combustion sources, such as candles and carbide lamps. When electrical lighting became the standard in homes, industry, transportation, as well as for portable lighting, reflectors remained the dominant optical component. For many of these applications, diffuse as well as directed or even sharp light patterns are required. All classic light sources (i.e. flames or bulbs) emit radiation into almost the full sphere of angular space. Most commercial LED packages are half-space emitters that have an emitting front and a non-emitting back side. This has led to a noteworthy renaissance of lens designs for LED lighting.

A reflector is an optical device that redirects incident light back to the side of incidence. Reflectors can have various surface finish qualities. The surface finish either causes specular reflection or involves scattering. As an optical component, reflectors have a reflective layer or coating (or multiple coatings) and a substrate to be handled and mounted to provide a base for the reflective surface layer. Examples range from a polished bulk metal block with electrophoretic surface coating to a metalized foil (think of a silver or golden first-aid blanket). However, transparent optical components can be used for reflective applications as well, when the conditions for total internal reflection (TIR) are being fulfilled.

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In the simplest case, a reflector will only reflect light but not transmit it: we consider this a reflective surface for simplicity. In contrast, the surface of a refractive optical component may transmit and reflect light and will be called a refractive surface (or interface) in the current context. While the more detailed physical description of reflection on either type of interface involves Maxwell's equations and understanding the importance of evanescent modes, it is not necessary to discuss it for the treatment of design principles within the scope of this paper.

1.1 Reflective surfaces

The reflection at a perfectly flat single surface (interface between two media) is described by the law of reflection. The degree of reflection – the share of energy or total luminous flux that is being reflected – is quantified by the value of reflectance. The subject of reflectance is more technical than a single scalar value, and a nomenclature has been created already in 1967 by Nicodemus [1]. The total integrated scatter is thereby a measure for the total (relative) amount of light scatter from a reflector that may be reflected in any non-specular way [2].

1.2 Refractive surfaces

When a refractive (visually transparent, dielectric) optical component allows the transmission of light, the refracted (transmitted) share of light follows Snell's law, while the reflected share obeys the law of reflection. The physics of refractive interfaces and the angularly dependent degrees of transmission and reflection are attributed to the law of Fresnel reflection. Refractive media are strongly characterized by their refractive index. A higher refractive index contrast will create a higher level of reflectance. Also, a higher refractive index will lead to different angular relations in Snell's law, which leads to the principle, reflectors made of transparent material are based on: TIR. This is an effect based on the physics of refraction and energy conservation. With Snell's law, there is a limit to the angle of incidence at which light can pass through an interface of two media with different refractive index from the higher indexed side toward the lower indexed side (i.e. from inside the optical component toward air). At an angle greater than the threshold angle (aka 'the light cone'), it cannot pass and will be totally reflected. This effect is wavelength sensitive according to the dispersion of the involved media.

The physics of reflection and refraction is well known, and detailed treatment of the topics and keywords touched in the above paragraphs can be found in many optics or lighting textbooks, such as in [3–5]. In addition, William Elmer has written a textbook based on lifelong experience in creating reflectors for lighting applications [6]. A contemporary and compact overview of illumination concepts and terminology can be found in the SPIE 'Field Guide to Illumination' [7].

1.3 Reflector devices

Reflectors can be of different device types. Depending on where and how reflection is being technically realized, we distinguish between first surface, second surface, and TIR. These should be considered as just the archetypes for optical components – the process of reflection on a complex multilayer metallic paint is much more complicated to describe.

1.3.1 First surface devices

First surface reflectors can be made of any type of substrate with a reflective coating on the front side, toward the optical system. The main advantage of first surface reflectors is the single surface interaction with incident light, which offers the highest image and lighting quality. Laboratory-grade reflectors or telescopes are typical examples on the high end, but most reflectors used in commercial lighting applications are also developed with this approach.

1.3.2 Second surface devices

Second surface reflectors are coated on the backside, which makes incident light pass through the medium before and after reflection. Additional Fresnel reflection occurs at the interface between the surroundings and the medium. For sensitive applications, this can create ghosts of first and higher-order source images. One advantage of this approach is the protection of the coating (which is on the backside). Consequently, practically all household mirrors are second surface reflectors. In lighting, they are used less often.

1.3.3 TIR devices

TIR devices are designed by arranging the angle of incidence at the reflector surface to fall into the total reflection regime of Fresnel's equations. Therefore, the seemingly transparent optical surface appears to the light inside the medium as totally reflective. The main advantage of TIR devices is that there is no need for any coating. In addition to that, there is always an entry surface of the refractive component and an exit surface. So, a TIR reflector (single reflection) will most often offer at least three surfaces that can be engineered to mold the flow of light, which may all be used for beam shaping without the need for an additional component: you may want to think of two lenses and a reflector – all made in one part. The disadvantage of a TIR device is its limited applicability because of the TIR effect's angular dependency. From a fabrication point of view, such devices are lenses because of their material's nature. However, their TIR surfaces should be treated as reflectors from a design perspective.

2 Materials and Examples

Substrates and coatings can vary from application to application and from budget to budget. While a wide range of coatings and substrates are possible, the following are descriptions of commonly used materials.

2.1 Substrates

2.1.1 Metal

Metal reflector substrates may appear as reflectors even without coatings. Polished sheet aluminum or stainless steel can be an adequate reflector material, but without a protective coating, the aluminum will develop an oxide layer over time. Therefore, metal-only reflectors are mostly used for price or decorative reasons when the optical requirement is simple. Coated metal parts are preferred to meet more stringent surface quality or high-reflectance requirements.

Robustness and heatsinking potential are two strengths of metal reflectors, while weight and cost are two weaknesses.

2.1.2 Glass

Glass is used less often for LED lighting, but it still offers some advantages over plastic materials. First, it can withstand much higher temperatures. It can be successfully used as a substrate for reflectors in halogen lights or in conjunction with other thermal sources. The design of glass reflectors is backed by a mature technology of creating and measuring extremely precise surfaces. Glass is often chosen for high-precision components, such as laboratory-grade optics.

2.1.3 Plastics

Whenever cost is a key consideration and neither temperature nor precision requirements are limiting, injection-molded plastics are likely to be the substrate material. Plastic substrates are the standard in automotive lighting, and many general lighting applications make use of them as well. In a process consisting of several steps, depending on the exact substrate and coating, the plastic parts are prepared for the metal deposition. Tight tolerances and requirements for a good surface quality narrow down the available substrate materials. The range includes high-temperature thermoplastics or reinforced duroplastics with pre-coatings. Thermosets such as bulk molding compounds are very cost effective but need special molding and injection (high pressure, short injection time) to achieve the necessary surface quality for a specular reflector. The surface quality depends not only on the material base but also on the process parameters controlling the mold flow. Not all coatings will stick to all plastics, pre-coatings may be necessary, and the quality of the reflective coating and its conformity with the designed surface can be affected by chemically mismatched paints and coatings. Advantages of plastic reflector substrates are price and weight, while the thermal stability and conductivity are limited. Three-dimensional (3D) printing has also entered the domain of optics for lighting, and even clear lenses can be fabricated directly by rapid prototyping techniques.

2.2 Coatings

2.2.1 Metal

Aluminum is by far the most common metal coating. Among deposition methods, physical vapor deposition, also referred to as vacuum deposition, is often used to coat a substrate with aluminum from the vapor phase. Vaporizing the precursor can be done by sputtering, electron beam, or heating. The vacuum prohibits oxidation for a good reflective coating and a homogeneous layer quality. Additional oxide layers are applied as protective outer coatings to ensure that the metal layer does not

Figure 1: Left: An aluminum-coated reflector on a lathe-processed aluminum substrate produces a simple paraboloid for flashlight applications with a specular surface. The base of the reflector is pressed against the ‘pill,’ its vertex hole centers the reflector on a specific type of LED. Right: Aluminum-coated plastic parts (play bricks) to illustrate the conformal coating with metal on plastic and to show the impact of a small surface contour deviation on the ‘beam pattern’ of reflected light. Sunlight is incident from the right in this photograph. The reflection of sunlight off the long brick on the bottom left shows distortions and artifacts caused by the surface contour which is not flat; the reflection by the right brick shows a smooth light distribution: its surface is flat.

age chemically. Not all metals will stick well to all substrates, and coatings for glass will be different than those for plastic substrates. Figure 1 shows examples for metal coated reflector parts.

2.2.2 Dielectric

Multi-layer coatings or dichroic coatings use dielectric thin films to create an interference-based reflectivity. A prominent example is the halogen cold reflector. Its coating is of dichroic nature and will let infrared radiation pass through the coated glass to the rear but will reflect the visible light out the front of the reflector lamp. Such multi-layer thin-film reflectors achieve high reflectance and quality. In addition, they can offer spectrally customized reflectivity properties or angular sensitivity, to name two unique qualities of these optical filters. Metal coatings on first surface devices usually have a protective dielectric layer on top.

2.2.3 No coating

TIR devices do not require coatings on the surfaces with total reflection. Examples of TIR optical components are the collimator LED lenses shown in Figure 2. Prisms and the more complex RXI designs [8] also use TIR as their mechanism of reflection. Nevertheless, complex parts may require a coating to eliminate stray light or to solve systematic problems at the point of in-coupling light into the part. Also, uncoated TIR and coated reflective surfaces may be combined within the very same refractive optical component.

Figure 2: TIR reflector examples: Collimator LED lenses are hybrid devices that use a front lens shape and a side reflector to direct light. The smooth paraboloid shape is the (freeform) TIR reflector of these components. These samples are made of PMMA through injection molding.

2.3 Surface quality

There are three archetypes of surface quality if we want to exclude non-random design textures for simplicity. Any real surface may be a mixture of each of them, depending on the exact structure of the surface. A fundamental paper on ‘Scattering effects of machined optical surfaces’ was written by Kotha and Harvey [9].

A reflector of specular surface quality is an archetypical example of the law of reflection. Angle of incidence for any ray equals the angle of reflection. A surface with this property is considered highly polished (model: ideal specular – law of reflection). Typical everyday examples of lower quality are flat household mirrors. A mirror without such a specular surface quality creates a blurred image.

Reflectors creating a certain directional light spread with their non-specular surface quality are using a randomly rough surface or an intentional texture to soften the exiting light distribution. A microfacet model [10], or any surface normal perturbation (statistically modeling the surface roughness), gives each infinitesimal part of the surface a different orientation and slope. The overall normal density distribution function often follows a Gaussian or quasi-Gaussian distribution. Therefore, they are often approximated by a Gauss-type scatter model, e.g. a Gaussian surface normal perturbation model. The exiting vector obeys the law of reflection on each microfacet, and the direction of reflected light depends on the angle of incidence. Typical examples are all reflective surfaces with a glossy finish, such as the rough side of a piece of aluminum foil used in the kitchen. Practically, measured optical scatter created by rough surfaces or measured surface roughness can be modeled by using a bidirectional scatter distribution function (BSDF), be that an analytic description (a formula), a microfacet model, or a lookup table with measured values from a goniophotometric investigation of a real surface sample. Correlations between surface roughness and light scatter are a subject of science and engineering of their own [11]. The subject of BSDF (or BRDF for reflection) is discussed widely – not only in lighting and optics but also in computer graphics [12].

Lambertian surfaces can be highly reflective, but their surface roughness or substructure will reflect any light into vastly varying directions in a diffuse and very wide spread. The direction of reflection is independent of the angle of incidence (model: Lambertian reflector). Typically, Lambertian surfaces appear white to the human eye, one example being matte white paper. Lambertian surfaces are the archetype of a truly diffuse reflector. In addition to micro-textured or painted surfaces, surfaces with coarse and clearly visible macro-textures are being used for design reasons in general lighting applications.

The impact of the surface quality on luminance, the dimension being $[L]=cd/m^2$, and in this context may be best viewed as the technical equivalent of the casual term ‘brightness,’ is an important aspect. By widening the beam pattern by adding surface scatter to the general direction of reflected light, the luminance is affected as well. Ideal specular reflectors will often appear only lit up within a limited angular segment of space – where the reflector will focus the beam pattern to (imagine looking into a flashlight with a specular reflector, much like the one in Figure 1). Lambertian or rough reflectors of the same shape illuminate a wider angular range in candela space ($[cd]=lm/sr$) than a counterpart of specular surface quality, simply because of the added light scatter, resulting in additional angular spread. Spreading the assumedly same amount of flux over a wider angular range will reduce the luminous peak intensity (the ‘max *cd*’ value) and thus the observable luminance from any given point within the lit up angular range (imagine a flashlight with a diffuse reflector). Luminance calculation is of importance not only for virtual prototyping or glare analysis but also for road luminance predictions from vehicle headlights or streetlighting [13].

Please be reminded that the quality of any result of optical simulations is tied closely to the quality and precision of the material data used. This includes also the surface quality or its approximation in a computer model.

3 Applications

In general lighting, reflectors can be found in many classic lights. Downlights, stadium lighting, bollards, streetlights, and other applications rely on reflectors to limit the spatial emission of the light or to create the desired beam pattern. Matte reflectors not only widen the beam pattern but also soften the lit appearance, i.e. reduce luminance while one is looking directly into the light. They simply enlarge the emitting surface. Specular reflectors do so as well, but in their case, not all parts of the reflector may contribute to large spatial segments of the beam pattern. Thus, a reduction in luminance is usually not achieved. Screens or diffuse baffles are often used instead of reflectors for interior lighting. For LED lights, lenses are used more often. Special lights may benefit from reflectors more than others. For wall washers, for example, reflectors allow a different design of the light and housing to get the LED mounting and emission vector off-axis. This can provide heatsinking advantages or allow the construction of a different housing. In general, if the main light output vector is off-axis from the emission vector of an LED, a reflector may be the first choice. A 90-degree setup, for example, can have a small aperture and visible footprint at a small depth, while extending to the side within a wall or ceiling. Accent lights may show less artifacts in their beams at high efficiency when using reflectors instead of thick lenses. Work lights or handheld torches can be designed with reduced glare for the observer by limiting the emission angle or softening the luminance without absorbing too much light. Flashlights come with lenses or reflectors. Lenses with moving parts can allow zooming (switching between a narrow beam and a wide flood distribution). Reflectors (static) can create a desired beam pattern (the spot), but still may let direct flux from an LED create a diffuse, soft, and wide illumination around the spot (the spill) without the need for moving parts. Streetlights can benefit from a full cutoff at any desired angle without the need for additional optical components. There are many applications for which reflectors offer performance and esthetic advantages.

Photovoltaic solar power plants and thermal solar concentrators are another major application of reflectors. While their principle working method seems to require just to focus incident sunlight, their design can incorporate many more aspects, such as tolerancing or uniformity of the absorber illumination or reaching the maximum concentration factor [14, 15].

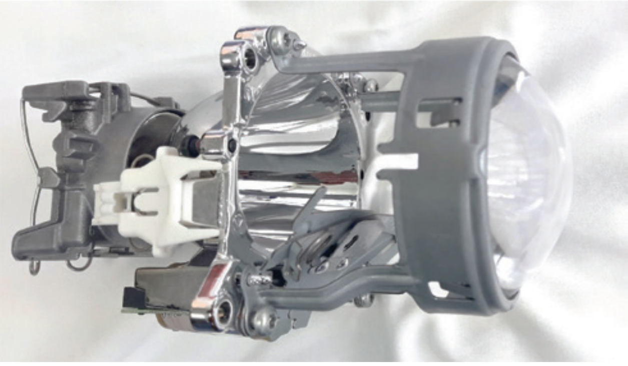

Figure 3: Projector-type headlight module, Bi-Xenon system (or bi-function unit), allows high beam to be activated by flipping the low beam shutter, using the same source (here missing: 35W HID Xenon). Working principle: The smooth, specular reflector is the beam-shaping optical element, and the aspheric lens is projecting the created beam pattern onto the road. Visible from the outside is only the lens, which makes up for a clean look.

In automotive lighting, reflectors and lenses have been used in combination since electric lighting and optical engineering came into widespread use [16]. Headlight units are composed of two main functions: low beam (dipped) and high beam (driving beam). Low beams using freeform reflectors are the standard approach, with LED or halogen sources. The performance per-cost ratio is very good, as the reflector is the collecting and beam-shaping device all in one. Low beams and front fog lights must have a cutoff to eliminate the risk of glare. Therefore, any design method to create a low beam can also be used for fog lights and require the tools to design a cutoff line in the beam pattern. The first matrix beam headlight (Audi A8, 2013 facelift model) was a reflector-based unit. Projector-type headlights like the one in Figure 3 have the outer appearance of lens-based designs. An aspherical lens is the dominant element in its appearance – but in the interior, there is, in almost all cases, a reflector unit for beam shaping. The lens is projecting the resulting image onto the road, and together, they create the headlight beam pattern. The unit in Figure 3 is an actuator-driven low-/high-beam bi-function module: it can provide low and low + high beam. The image shows the shutter in high beam mode. Even if a low beam unit is of projector type, high-beam units on the same car are often reflector designs. The reflector collects the light and creates the necessary luminous intensity for a high beam. A clear outer lens then provides protection of the unit. Even in laser high-beam units with the look of a lens module, a reflector may be doing the actual beam shaping. In addition to that, high-flux laser-activated remote phosphor light engines will benefit from an internal reflector design as well [17]. Signal applications are often designed with freeform outer lenses to have a single part and reduce cost and development time. However, since design is a driving force of car sales, clear outer lenses, additional inner lenses, and additional reflectors may be combined to create a tail light or turn indicator that matches the car design much better than other and possibly more efficient optical approaches. Interior reading lights are a good example of an application that leverages freeform design methods. In principle, close to general lighting applications, the reading light illuminates only a small surface area in the car. At the same time, any glare to the driver must be reduced or avoided completely. Quite often, the light guides in automotive exterior and interior lighting are backed up by reflectors to soften any light traveling back into the compartment and to diffuse out all artifacts (highlights, streaks, shadows, and so on) that would otherwise disturb the perfect visual appearance of the car or the illumination of its interior.

4 Design principles and methods

The design of reflectors can be approached directly via their mathematical descriptions, which is covered in the technical literature or via certain principles or computer-based methods of creating their optical shapes based on this mathematics. Since most optical and illumination design today is done in the computer, this article will touch on this general subject first and in the following name some other principles and concrete methods that may be considered representative for different approaches to transform the idea of an optical engineer into a reflector surface for production. Please be reminded that there are many more design concepts and algorithms in use today than this overview can collect.

4.1 Computer-assisted lighting

The three basic building blocks of computer-assisted lighting (CAL) or computer-assisted lighting design are the following:

- Create: Geometric surface design and optical materials definition
- Simulate: Predict the output and results of a lighting system in the computer
- Evaluate: Run result analysis and apply performance metrics or regulation tests.

There are more aspects and special tools in modern CAL software, such as tolerancing, CAD data exchange tools, expert systems for fast feasibility studies, and many more. However, the above three elements are part of the core cycle in lighting design: create, simulate, evaluate.

The creation of optical geometry will be the dominant aspect in this section on design principles. This section will treat examples from illumination optics only and use references to general and automotive lighting. Methods from imaging optics will not be discussed beyond brief mentions – for this field, please refer to the existing literature, for example, Brömel's recent thesis with a widely scoped overview on the subject [18].

4.2 Source alignment

One fundamental question is independent of any electronic design support but is a systematic one: the question of 'alignment,' which is closely related to the terminology of 'direct vs. indirect.' If a reflector design is controlling all the emitted flux from the source, then the design is indirect. If some flux is missing the reflector and contributes to the output beam pattern, this share of flux is direct. Indirect flux is always the share that is under control in a reflector design, as it can be shaped by the reflector. The direct flux may still contribute intentionally to the beam pattern and should be considered during design. However, in cases where this is not allowed, direct light must be blocked or the reflector must be large enough to receive the complete flux.

Indirect designs offer higher light control: more or all flux is caught by the reflector for collection and collimation or directly for image formation and creation of the beam pattern. Related to the topic of direct or indirect design is the topic of 'on axis versus off axis.' This refers not only to the position of the source but also to the alignment of its optical axis with the optical axis of the reflector. This topic is discussed at length in industry publications [19]. The desired degree of flux control is often the requirement to choose a purely indirect setup. The size and position of a reflector control and limit its ability to collect light. Unfortunately, the freedom to set the parameters for both properties – size and position – are often limited in lighting design.

4.3 Classic form versus freeform

Classic optical shapes include forms such as sphere, parabola, and ellipse. They all are based on an analytical formula that reflects the nature of the form. This formula allows the use of focal points or other classic design principles of geometric optics. In contrast to this, freeform surfaces are variably defined and cannot be described with a single analytical formula. However, this definition of 'freeform' is subject to the field of work. For illumination design, a freeform optical shape is often described as 'piecewise,' defined as, e.g. a segmented reflector with so-called pillow optics as a modulation of an otherwise parabolic base shape. In imaging or beam-shaping optics, freeform is referred to rather as optics without certain symmetry, e.g. being without any rotational symmetry – such components cannot be produced on a regular lathe but may require for example a high-speed single-point diamond turning technique. For classic forms, the rules of geometric optics link focal points and radii, surface normal vectors, and the law of reflection to a well-understood subsection of modern physics. They cover solutions to a wide range of problems, and many components are available off the shelf. Replacing classic forms with freeform solutions not only allows creation of reflectors for a much wider range of beam patterns but also allows correction of optical errors and achieving a higher beam (or imaging) quality. For complex beam patterns, a finer surface curvature control is required, in conjunction with a local or piecewise variation of the same. Today's freeform surfaces are often based on non-rational uniform B-spline, a mathematical definition of curves and surfaces that allows a wider range of optical contours than classical analytic expressions. Instead of using an analytic formula, a set of control points and other parameters (knot vectors, weights) can be the foundation of a surface. Figure 4 in the paragraph on procedural surfaces shows a simple classic paraboloid reflector along with a typical illumination-oriented freeform version of it. An overview of the field can be found in Winstons's textbook [20].

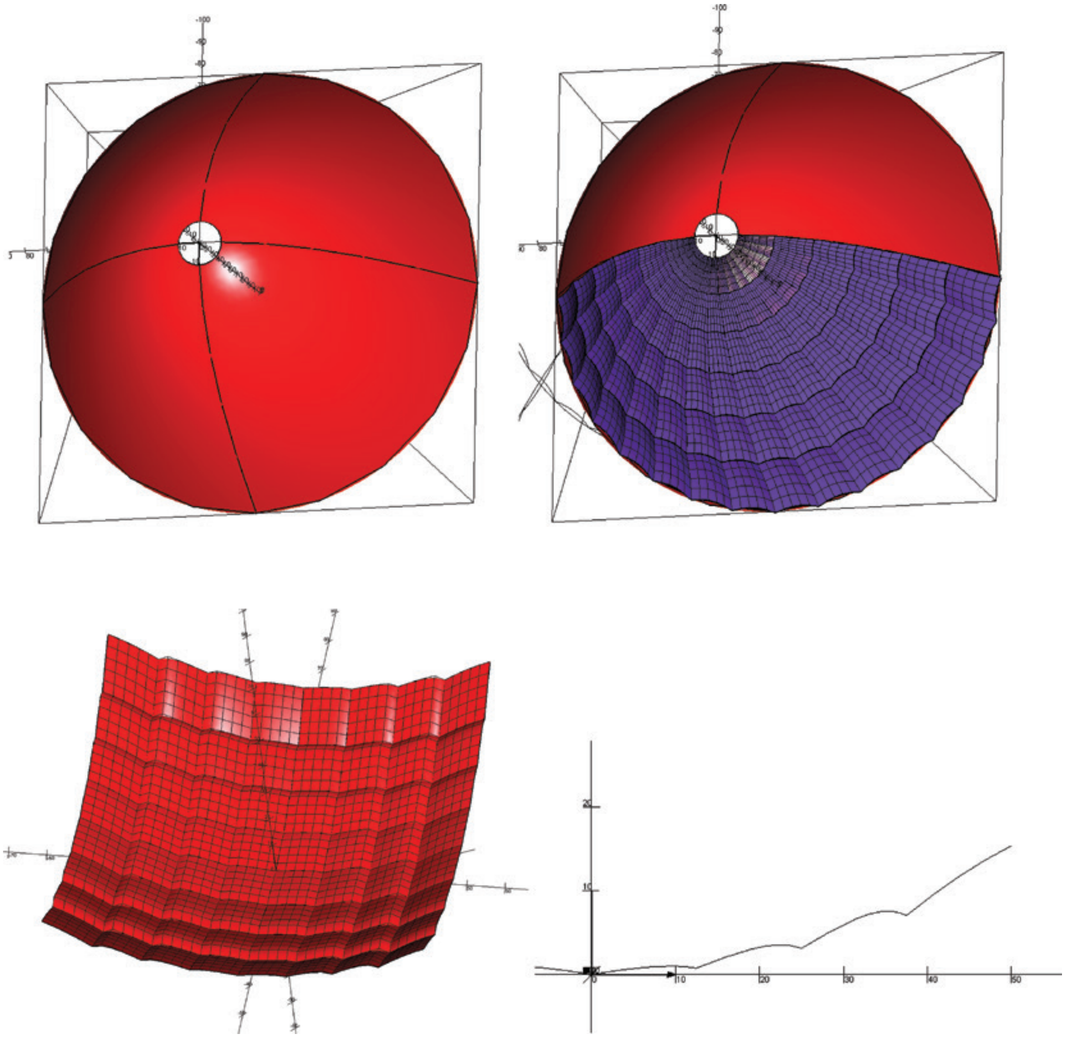

Figure 4: Classic and freeform geometry. Top, left: Simple parabolic reflector shape characterized by vertex position, dimensions, and focal length. Top right: Procedural surface based on the same paraboloid base surface (red), but with added 'design by function' surface modulation for controlled light spread (pillow optics, purple). Bottom: Procedural surface created from two reflector profile curves and a procedural CAD operation (such as sweep, rail, or extrude). Bottom left: The calculated reflector surface in 3D geometric view; this is an 8 by 8 faceted reflector for ±20° and ±15° of light spread. Bottom right: One of the profile curves in cross-sectional 2D view using a smooth connection between the segments, creating additional light spread in this example.

State-of-the-art freeform design approaches often incorporate built-in physics or optimization routines into the actual layout process for a reflector shape. In addition, parallel to the possibility of a purely geometric creation and a brute force optimization of the potentially huge parameter space, there are more sophisticated approaches to calculate freeform surfaces in lighting engineering. They are all well suited for certain problems and applications. A recent overview of freeform illumination optics and the mathematical methods to create them was published by Wu et al. [21]. The methods briefly described within this article on reflectors use one-to-one mapping approaches for the calculated smooth single surfaces. These single surfaces may be the individual building blocks of faceted or segmented reflectors. Most freeform optics provide solutions to either a target illumination in far or near field. However, for design reasons, approaches toward the mathematical solution for illuminating an aperture uniformly were developed in the 1970s [22], leaving the control of the final light direction to established components, such as prismatic lenses.

4.4 Chip images and dimensions

It is always important to keep the absolute and relative dimensions of any lighting system in mind. The source's relation to the optics is responsible for the magnification and has an effect on how small or large the source images will be that a certain spot on the reflector can provide to 'paint' the final beam pattern. Using filament or chip images to paint fine details into a beam pattern is only possible if the optical components offer a sufficiently large space and distance to the source. Searchlights are the archetype of this principle: the larger the reflector (the further it does extend from a given source), the longer the range can be (i.e. the higher the peak luminous intensity will be). Automotive headlight engineers may struggle to balance design requirements for flatter, smaller headlight compartments with the necessary optical performance. Today's headlights are becoming flatter and narrower per design – while the engineer's headlight design paradigm insists on the contrary: the longer the north curve, the better your low beam will be. The 'north curve' represents the part of the reflector that creates the cutoff line, particularly for projection-type headlights. If it is too small or too close in relation to the size of and distance from the source, the cutoff line between light and dark in the low beam pattern might not satisfy the legal gradient requirements in a mass-produced reflector. A good headlight beam pattern will be smooth, artifact free, wide enough, and, of course, fulfill all regulations. A better headlight low beam has a skillfully crafted cutoff line and beam pattern that create an improved effective obstacle detection range on the road by using fine source images close to the cutoff line to generate extra range. Recent on-road tests by the US American Insurance Institute for Highway Safety (IIHS) are trying to use aspects such as range, illuminance monotony, and glare dosage for practical headlight benchmarking. Please refer to [https://www.iihs.org/iihs/topics/t/headlights/topicoverview] for details on the IIHS 'Headlight test and rating protocol.'

4.5 Manual design

Optical engineers are still using manual definitions of optical surfaces, using CAD tools to create surfaces for reflectors to simulate the results and run iterations in a trial-and-error cycle until the solution is satisfactory to their performance goals. This basic concept has not changed much and follows the cycle of the three steps introduced in the earlier section on CAL: create, simulate, evaluate. Knowing an application and a software tool well, this method can solve many problems in lighting design. However, when it comes to more complex or precision-demanding problems, the time and effort required will most probably exceed a project's time frame. Therefore, more sophisticated methods have emerged to speed up the design process. This can be achieved in two ways: (1) reduce the time per cycle and (2) reduce the number of cycles until the final solution is found. There may be one exception to this rule when using optimization techniques.

4.6 Design by function

A design by function method belongs to a class of techniques that allows the optical designer to define a desired lighting target instead of defining the geometric surface itself. It eliminates the need to define geometric surfaces in CAD by their surface definition but allows the engineer to work in candela space (i.e. aiming angles) or on a target illumination surface – or to think in section curves and beam width. Also, reflectors that are designed with a virtual focal plane as a reference approach may be used to reshape the emission of a source so that it appears to be further away from a second optical component. This design by function approach is a method to reduce the time per cycle, as the optical engineer is relieved of some trial and error in form of the calculus of the law of reflection and the surface curvature/normal, and instead can 'think' in target space. From the engineer's perspective, a specific facet on a segmented reflector could be defined to spread light from –10° to +10° horizontally by defining these targets. Then, the law of reflection is used to calculate the necessary curvature based on the definition for the desired light output directions, a point or surface for a source reference position, and the desired basic shape and position of the reflector to start from. Then, the resulting geometric shape is calculated by the computer in an instant. This is different from using an analytic formulation of an optical device: for example, the focal length description of a simple paraboloid does provide a very small parameter space for describing its shape by using an optical definition. Using a design by function method not only reduces the parameter space but also translates freeform surface mathematics into the language of a lighting engineer: the far- or near-field illumination target definition. A mathematical treatment of how to derive a symmetric reflector curve's tangent with respect to source and target was published by Zhao [23].

4.7 Design by optimization

The principle approach of using optimization techniques does speed up the design cycle in a very specific way.

Generally, it reduces the time per cycle by eliminating the need for user input and evaluation, thus speeding up the cycle. It does not necessarily reduce the number of cycles, but it does something more dramatic: after being set up correctly, it keeps working without the attention or oversight of the engineer. This can be helpful to allow the engineer to work on another aspect of the project at the same time. However, it can also extend the effective working time during lunch breaks, overnight, or over longer periods, such as weekends. Optimization may be an exception to the rule stated in the earlier section on Manual design, which claimed that either the cycle time or the number of cycles can be impacted for the better by choosing the right design method. Optimization has an increased value for time-consuming tasks with many iterations but clear merit functions that allow minimum oversight. A prominent example would be the design of light guides, where dozens or hundreds of prismatic facets need to be placed, sized, and oriented, or the design of uniform illumination targets.

4.8 Method: procedural surfaces

A simple but effective optical design software method is the combination of 2D profile curves (or light spread control curves) and CAD processes to create surfaces. The 2D curve definitions are created by a design by function approach or by a special algorithm and are subsequently applied in procedural operations such as sweep, rotate, or extrude to create an implicit definition of the desired surfaces. Therefore, the created surfaces are addressed as procedural surfaces. This method is fast but will still leave the overall beam creation (the 'bigger picture') to the skill of the optical engineer. Also, it has only limited freeform capabilities, as the procedural operations and the usually limited number of profile curves reduce the parameter space to a subset of what is possible. Further, certain symmetry rules may be implied by a specific procedural operation, the repetition of pillow optics along a parabolic curve can, for example, be still shaping a rotational body. A very simple example would be the use of a parabola curve ($f(x)=x^2$) and a rotation operation to create a rotational paraboloid (see Figure 4, top left). The same curve in conjunction with a symmetric extrusion operation would produce a trough reflector instead. However, the greatest value may be the ability to define local facets (or pillow optics) by dividing up the reflector curve(s) into subsegments with individual design targets. Figure 4 below shows examples of such procedural surfaces. Typical applications for this method include faceted reflectors of automotive signal lights, reflectors in interior downlights, streetlights, and many more.

4.9 Method: base grids

Often, a classic optical shape provides the basic outline or shape of a reflector. Even if there is a highly technical faceted surface on the front, the average contour may be a paraboloid because of tradition, styling, or light collection. For a higher degree of freedom in choosing shape, distribution, and position of individual facets or regions of a reflector, a different base for the calculation of the reflector surface can be used. We refer to this as the base grid. An example for such a base grid is shown in Figure 5. This terminology originated in automotive headlight design. In the past, a to-be-designed light lens was composed of different glass shards, put together and reassembled in many trial-and-error sessions in the lab, until the final shape was found. A tool would then be created to mass produce the final solution. However, the grid, the arrangement of the shards or facets, would of course still be visible in the final product. Nowadays, a base grid is a numerical outline of the individual subsegments of a reflector, the so-called

Figure 5: Classic headlight lens made of glass for low- and high-beam creation, showing the traditional shard grid where each facet serves a specific purpose; contrast-enhanced black and white photograph. Each shard is nowadays a single freeform surface facet to be designed and calculated individually with respect to the other facets and their contribution to the combined beam pattern. This original sample was designed for a dual-filament bulb.

facets (shards). Often, their arrangement does not just follow function but is required by defined styling lines. A large number of options give this method a wide range of applications. Additional options allow the engineer to connect multiple facets to a large segmented reflector entity. In contrast to procedural surfaces, each facet here will be calculated individually by sampling the solution of a design algorithm. All the facets then will be connected to their neighbors according to special rules to form the final surface shape or to be closer to tooling requirements such as radii or draft angles. The strongly extended freedom in design and fabrication-oriented development makes this approach widely used in automotive headlight and tail-light design, but also leaves it of great value to designers in general lighting where the appearance of the product (lit or unlit) is a key factor as well.

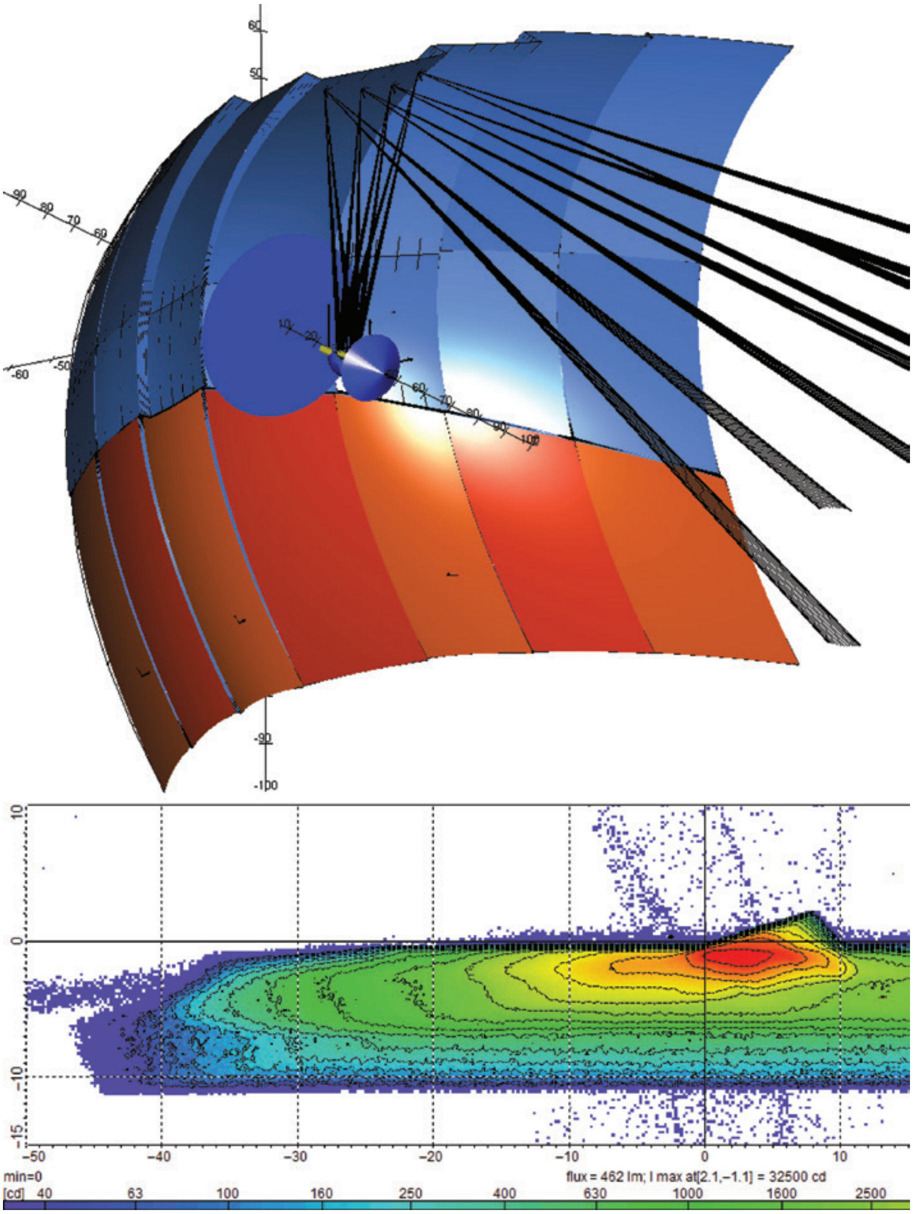

Figure 6: Automotive headlight setup based on an old H4 dual-filament bulb – for low beam, the LB coil is active, for high beam, only the high-beam coil will light up. The reflector is made of two parts for low beam/high beam and high beam only. This layout is being set in the so-called base grid, the underlying segmented structure of the reflector (driven by styling lines and optical strategy). The upper (blue) part of the grid is the low-beam reflector, the lower (red) part is for the high beam only. The tricky part on a dual-filament design is that the low-beam reflector will also be illuminated by the high-beam coil. The same algorithm is being used for LED-based low-beam reflectors but uses different base grid layouts [LucidShape Macrofocal Module].

4.10 Method: macrofocal

As the name indicates, the macrofocal method takes into account the size of an extended source: instead of a point source, the computer will use the edges of the light source model to calculate optics. In particular, the concept of using edge rays for surface design is important [24]. The source images can be arranged to aim by the center or edges of the image (to allow sharp contrasts along one side). An underlying base grid provides the framework for sampling the calculated reflector surfaces, as stated in the section above. One of the major applications for this method is the design of low-beam headlights, since they require a defined cutoff line in the beam pattern to avoid glare – and, practically speaking, to have the sharp edge between light and dark as a visible marker to allow reasonable headlight alignment. A classical H4 dual-filament bulb reflector design example is shown in Figure 6.

In his 2010 thesis, Fournier offers a wide overview and detailed treatment of this subject [25].

4.11 Method: freeform designer

The next level of complexity is the freeform design approach. Obeying certain user-defined boundary and acceptance conditions, the computer will shape the contour of the reflector (or lens) based on known source emission characteristics and the desired target definition. The target light distribution can be in angular or spatial domain. Essentially, the reflector surface will be solved piecewise on a point grid, and then, the point grid is interpolated to create the optical surface. Depending on the desired contrast and beam pattern, the point grid may be coarse or fine. The required grid resolution depends on the size of the source, since the use of an extended source will blur the result of the calculation compared to a point source. Some freeform design algorithms incorporate the source dimensions directly into the optical calculation, and others assume a point source. The result of the calculation is a ready-to-use freeform surface delivering the desired beam pattern. An example for the improvement of collection efficiency was published by Jacobsen and Cassarly in 2016 [26]. Figure 7 illustrates an example reflector designed with this method.

There are other methods in use for optical design, such as using wave-front tailoring to calculate two surfaces that are not independent in their calculation within the same optical system. Examples of freeform optics for illumination with the 3D SMS method were published by Minano et al. [8] or for example by Dross et al. [27]. Independent of the mathematical method used, the literature and number of successful projects in the field of freeform design using mathematically advanced software tools are growing.

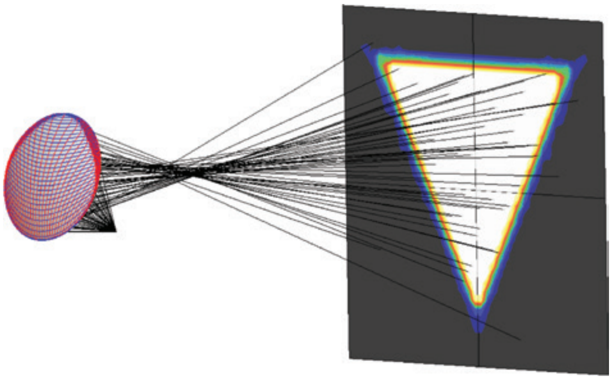
Figure 7: Freeform designer example illustrating a beam pattern with a spatial target definition displaying good contour contrast. This calculation was based on a point source, but extended sources are also possible.

The choice of a design approach depends on the desired beam pattern, the working principle of the lighting setup, the source, the available packaging area, the budget, the required efficiency, what type of reflector surface, the material, and the quality are chosen. It is best practice to investigate the limitations of available design and fabrication techniques to make sure that the designed optical shapes can be fabricated as needed – or that the design methods are chosen with respect to an already selected material base or fabrication technique.

5 Conclusion

The design of reflectors for lighting applications includes a wide range of optical solutions, materials, mathematical models, and engineering techniques. Design methods today make use of simple classical optical shapes as well as sophisticated mathematical models to create freeform surfaces in a way that is time efficient for the optical engineer. The choice of a design method will be driven by the required functionality, but may also be strongly influenced by the design language.

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