ABSTRACT

In illumination systems, the look and feel are often more important than objective criteria, such as uniformity and efficiency. The reason for this is two-fold: the lit appearance often sells an item and substantial variation in the illumination distribution (up to 50%) over a broad region is not noticeable to an observer. Therefore, subjective criteria, such as the lit appearance, typically play a crucial role in the development of an illumination system. Additionally, by using computer models to ascertain the lit appearance before manufacture of the system, it allows the designer to modify the system while not demanding investment to produce prototypes. I discuss methods of determining the lit appearance for illumination systems. This modeling includes the inclusion of material and surface properties, such as surface finish, spectral transmission, and internal scattering; the response of the human eye; and the amount of rays that must be traced. By archiving the ray data, animations as a function of position and angle can be developed. Examples are developed to highlight the utility of this technique. These examples include taillights for the automotive industry and a backlit LCD screen for a laptop. Animations of these models demonstrate their luminance.

Keywords: Illumination, rendering, lit appearance, unlit appearance, optical design.

1. INTRODUCTION

An optical designer is typically concerned with how well an optical system performs, such as with the MTF and PSF characteristics, the aberration content of an image, color reproduction, and so forth. In illumination systems, the designer is also highly concerned with analogous parameters, especially the ability to meet a desired illumination distribution and the transfer efficiency. However, subjective criteria often play a larger role in illumination system “performance”. These criteria are based on the lit and unlit appearance. The unlit appearance describes what the illumination system looks like in daylight situations, i.e., when there is no active illumination coming from the system. The lit appearance defines what the illumination system looks like in a dark situation, especially those whereby the illumination system is being used for its intended function. These two appearances are used to differentiate one’s design from another’s. Or in other words, these subjective appearances are used to both market and sell the system or the product to which the system is attached (e.g., headlights on an automobile). It is virtually impossible for the illumination designer to quantify the impact of the lit and unlit appearances in the design process, but the designer can work hand-in-hand with the stylist to provide a desired look and feel in addition to functional performance. Such a design process will have both objective optimization processes and subjective one. In the objective steps the illumination designer will address the required illumination characteristics, such as uniformity and efficiency. Such steps can be done through user-involved modifications to the design or via an optimizer. The subjective steps are done in concert with the stylist. Typically the goals of the two different steps run counter to one another, so there is a degree of compromise that needs to be built into the process. After several iterations the final design will at a minimum meet required standards, but have a compromise between the original desired look and feel and the beyond standards technical goals.

The benefits of determining both the lit and unlit appearances are: the designer and stylist can work together in a virtual environment before expensive and time-consuming fabrication, the effects of many and variable changes to the design can be studied quickly, one can investigate the tradeoffs between the technical and visual desires, and it provides a cheap, but effective, marketing tool. Additionally, the human visual system does not respond to slow variations in the illumination distribution, even when the overall variation is upwards of 50%. By including this reality into the technical design process, one can potentially reduce the overall cost of the illumination system. Finally, while the illumination...
system must meet the minimum standards requirements and the like, it is the appearance of the product that sells it. The illumination designer must always remain cognizant of this aspect.

The unlit appearance can play a large role in the marketability of an illumination system; however, it is the lit appearance that often makes the “sell”. There are potentially a multitude of methods to determine the lit appearance for an illumination system. A system based on archiving a ray set in both position and direction is discussed herein. The directions, positions, and fluxes for the rays must be retained in order to understand the lit appearance as the view angle and position of view is changed. This technique lends itself to creating animations as the viewer “walks” around the illumination system. Additionally, since we assume a human visual system, the response of the human eye must be considered. The human eye responds logarithmically to light and can typically distinguish around 2.4 orders. These parameters are used herein to set up lit appearance models. The models studied herein are automotive taillights and backlit LCDs, especially screens for laptop computers.

In the next section is a brief discussion of the theory basics in order to determine the lit and unlit appearance. Included in this discussion is a brief overview of the software components to the modeling. It is not the purpose of this paper to be the definitive source for appearance modeling, but, rather, a discussion of a method to do such. Within the next section are examples of unlit appearance. The third section describes examples of lit appearance. It is not possible to show animations of the lit appearance in a proceedings format; so individual frames are presented in order to convey the point. Finally, conclusions and future work are discussed.

2. THEORETICAL BASICS OF APPEARANCE CHARACTERIZATION

The two types of appearances are briefly described herein: lit and unlit appearance. Unlit appearance is discussed first followed by lit appearance. Both techniques use the same type of algorithms, and the goal for each is to give the designers a better understanding of the look and feel for the systems prior to fabrication. Additionally, a prime motivator for the lit appearance is to develop an accurate model of an illumination system’s light output characteristics.

2.1 Unlit appearance modeling

Unlit appearance is typically determined with rendering engines. There are essentially two methods to render: ray tracing and radiosity. Of course within each method there are a number of distinct algorithms, and additionally, there are combinations of the two techniques. Ray tracing algorithms simply trace rays from the objects in the scene to the observer. They typically involve limited object-to-object interactions and a reduced set of optical properties (e.g., refraction is simplified) in order to make the algorithm quicker. Radiosity algorithms use surface scatter properties (e.g., BSDF) in order to propagate flux from the objects to the observer. There is still a limited amount of object-to-object interaction, but the nature of the method makes it faster to “trace” than ray-tracing methods. Note that ray-tracing rendering methods are better suited to scenes involving specular surfaces, while radiosity is more appropriate for scenes with diffuse surfaces. There is a large number of software packages that can do rendering, both ray tracing or radiosity. For the purposes of this study, Rhinoceros® or its associated rendering engine Flamingo® were used.¹

The steps to render a scene are: setup of the geometry, assign optical properties to the objects (including refraction, reflection, absorption, scattering, and color), develop and locate the illuminators, and render the scene. For the unlit appearance, the second to last step means the illumination source is located typically external to the objects that you have developed. For the lit appearance, the same step means the emitter within the scene generates the only light in the rendering. External light is not included in such renderings.

In Fig. 1 there are several renderings of illumination systems: (a) D2S bulb, (b) sodium deposits in the D2S bulb, (c) HB3 bulb, (d) red traffic light, (e) LED, (f) star-shaped taillight. The complexity and rendering quality of the various systems varies; however, the more recent renderings are shown first followed by older renderings. This historical perspective shows the increased abilities over the past years of the rendering engines.
Fig. 1: Renderings of (a) D2S bulb, (b) deposits in (a), (c) HB3 bulb, (d) traffic light, (e) LED, and (f) star-shaped taillight.
2.2 Lit appearance modeling

Lit appearance modeling is best served with ray-tracing algorithms. Analogous work in the imaging field has been presented recently. As mentioned previously, there are a large number of software packages that can provide such; however, the desire is to model accurately the luminance distribution resulting from the illumination system. In order to do such, optical analysis codes based on the scientific principles of light propagation are the logical choice. Advanced Systems Analysis Program (ASAP™) is used for the lit appearance modeling described in this section and the next. The same technique described in the previous section is used to generate a rendering of the lit appearance. First, the objects in the scene are developed (most likely in the CAD program used in Section 2.1). Optical properties are assigned to the objects. Next the source is setup within the object space. Lastly, rays are traced from the emitter till they are emitted from the transmissive output aperture of the illumination system. At this point the positions, directions, and fluxes of these rays are archived for later data processing – the rendering process.

The rendering process generates scenes of the illumination object dependent on view angle, spatial resolution, angular resolution, and total field of regard. For any view angle, the observer captures a prescribed angular cone of light, which is usually the angular resolution. This capture angle is related to the distance between the observer and the illumination system. Typically, the capture angle is between 0.3 degrees and 15 degrees. Thus, the higher the spatial and angular resolution desired, the larger the number of rays that needs to be traced to ascertain the luminance distribution. A rule of thumb is to capture at minimum 10 rays per spatial pixel and angular pixel. For example, if the spatial resolution is 100 pixels by 100 pixels while the angular resolution is 50 pixels by 1 pixel (i.e., only viewing in one direction), then at minimum five million rays need to captured at the output aperture of the illumination system. The combination of the spatial and angular pixels are called “bins”. Next, the binned rays are processed within a certain capture angle by projecting them into space along the desired view angle. This process is iterated till all scenes dictated by the field of regard and angular resolution are generated. During this step color is added to the scenes by selection of a palette. Multi-color scenes can be generated by processing each color separately and adding the results together at the end. Finally, an animation of the lit appearance as a function of angular resolution can be developed.*

During the rendering process one must account for the response of the human eye. If this is not done, then unrealistic images will be generated. The human eye responds logarithmically to light, and it can see in the range of two to three orders of magnitude at a given time. The accepted norm is about 2.4 orders of magnitude. This response plays a large role in the generation of images as depicted in Fig. 2. Four examples of arc lamp emission are shown. The first shows a linear false-color plot, while the other three cases show logarithmic responses of 1 order, 2.4 orders, and 10 orders. Thus the human eye will see an image analogous to that of Fig. 2c, while the others provide false representations of what the eye will see.

Fig. 3 shows the lit appearance of the star-shaped taillight of Fig. 1f. The view angle is 0 degrees with a 12-degree capture angle. Within this capture angle 101,499 were processed out of an original one million. The “bright” center is light directly from the filament. In the next section a taillight and a backlight display are presented at a few view angles.

3. EXAMPLES OF LIT APPEARANCE MODELING

Two examples are highlighted during this section: an automotive taillight and a backlight display. The modeling described in Section 2.2 is used. In both cases animations were developed, so frames from these movies are presented.

3.1 Hexagonal taillight

The first example is a hexagonal taillight. The animation generated ranged between view angles of 0 degrees to 30 degrees. Thirty million rays were captured over the field of regard and 15 scenes were captured over this range, thus the angular resolution was 2 degrees. Fig. 4 shows four views of this taillight: (a) 0 degrees, (b) 10 degrees, (c) 20 degrees, and (d) 30 degrees. This design does not yet meet governmental standards (e.g., SAE), but it does allow the stylist and designer to make look and feel changes prior to addressing the final aspects of the technical requirements.*

* During the presentation, animations of the lit appearance of illumination systems were presented. These animations were two taillight examples and a backlight display. Static images at different view angles are presented within this paper.
Fig. 2: False-color plots of the emission from a D2S arc lamp: (a) linear scale, (b) logarithmic with one order plotted, (c) logarithmic with 2.4 orders plotted, and (d) logarithmic with ten orders plotted.

Fig. 3: Lit appearance rendering of the star-shaped taillight shown in Fig. 1f at 0-degree view angle.
Fig. 4: Four view angles of a hexagonal taillight: (a) 0 degrees, (b) 10 degrees, (c) 20 degrees, and (d) 30 degrees.
3.2 Backlit display

The next system modeled was a backlit display found in LCD screens. An 11.1-inch diagonal display was modeled in software, and it is shown in Fig. 5. The source is a cold-cathode fluorescent lamp (CCFL) with a 2-mm bore diameter and 4-mm total diameter. The CCFL is coupled to the lightguide with a parabolic-shaped reflector with 85% specular reflectivity. The lightguide was acrylic plastic of 5-mm thickness at the aperture of the reflector. It was wedged such that at the end furthest from the CCFL the thickness was one millimeter. In addition to the wedge, to eject light from the top surface of the lightguide microstructure roughness was placed on the bottom surface of the lightguide. Additionally, below the roughened surface, a Lambertian reflector diffuser was placed to return light that transmits through the roughened surface. The end of the lightguide is vacuum metallized to return any light that propagates all the way through the lightguide. The inclusion of this metallization increases the efficiency of the lightguide. Finally, polarizers and the LCD cells are placed above the output surface of the lightguide. Three million rays were traced through the system, and of those 2.8 million were captured at the transmissive output aperture of the display. Fig. 6 shows the irradiance distribution at this output aperture. Due to absorption losses, polarization losses, and leakage the overall efficiency of this example is 34% while the uniformity of the useful region of the display is ±28% around the mean. A total uniformity variation of 56% would be observable, but for the purposes of this study it is satisfactory, especially since the optimal design of the display is not the focus of this investigation.

Fig. 5: Layout of the backlit display.

Fig. 6: False-color plot of the irradiance distribution at the output aperture of the backlit display of Fig. 5.
Next an animation of the LCD was created with a view angle range of 0 degrees to 60 degrees. Thus 30 frames are generated at the stated resolution. Fig. 7 shows four of the frames of this display: (a) 0 degrees, (b) 20 degrees, (c) 40 degrees, and (d) 60 degrees. Note that the spatial resolution of this image is not great enough, and obviously not enough rays have been captured yet at the output aperture. Also note that the capture angle is 15 degrees for each image yet the angular resolution is 2 degrees. The disagreement between these two angles allows for better scene visualization but at the expense of accuracy. To model a 640 by 480 LCD display over 60 degrees by 30 degrees at 2-degree increments, nearly 1.4-billion rays will be required.

Fig. 7: Lit appearance of the backlit display: (a) 0 degrees, (b) 20 degrees, (c) 40 degrees, and (d) 60 degrees.
4. CONCLUSIONS AND FUTURE DEVELOPMENT

Appearance modeling, both lit and unlit, of illumination systems is a crucial stage in the development of such systems. It allows both the designer and the stylist to interact and develop a desired look and feel while maintaining technical demands including standards requirements. Additionally, this virtual environment allows optimization prior to costly and time-consuming fabrication. It is an important tool in the repertoire of illumination designers.

Unlit appearance modeling will make use of rendering engines; therefore, advances in those software packages will allow improvements in unlit appearance modeling. There are a number of improvements that can be made to lit appearance modeling. Alternate tracing methods that propagate with a radiosity algorithm could be implemented in conjunction with the ray-tracing algorithm. This improvement has the potential to speed up the process, especially in light to the over 1-billion rays required to model a 640 by 480 LCD display with 2-degree angular resolution. The LCD example also by its nature encourages the modeling of a three-color display. Text and pictures can be included on the virtual display screen, and the lit appearance can be determined. This result would be very attractive to display manufacturers for both technical and marketing purposes. Finally, comparison of the lit appearance technique described here to rendering software packages would be useful. It would be interesting to compare the scientific packages with the commercial rendering packages.

ACKNOWLEDGMENTS

I would like to thank Mark Kaminski, Michael Frate, and Michael Stevenson of Breault Research Organization, Inc., who developed most of the renderings in this paper. I would also like to acknowledge the work of Don Scott, formerly of Breault Research Organization, Inc., who developed the application that made the lit appearance animations presented during the presentation of this paper.

REFERENCES

1. Rhinoceros and Flamingo are registered trademarks of Robert McNeel and Associates, 3670 Woodland Park Avenue North, Seattle WA 98103; www.rhino3d.com.
3. Advanced Systems Analysis Program (ASAP) is a trademark of Breault Research Organization, Inc., 6400 East Grant Road, Suite 350, Tucson, AZ 85715; www.breault.com.