Illumination Engineering

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Illumination engineering is a field that spans many topics, including the development of sources, design of luminaires and lightpipes, measurement of lighting conditions, and machine vision. The number of industries actively working in the field of illumination is also expansive, including: automotive, displays, general lighting, consumer, lithography, architecture, and bio-optics. Current sectors driving the envelope of illumination engineering include solid-state lighting, liquid crystal on silicon displays, photovoltaics, organic LED displays, daylighting, energy efficiency, and biomedical applications of lighting.

The previous paragraph illustrates how pervasive illumination engineering is in our daily lives. We depend on lighting in order to function: from lighting our offices to illuminating the roads for nighttime driving to illuminating the displays of the computers on which we depend so heavily. The two most common factors in illumination system design are efficiency and uniformity of the distribution. In regards to efficiency, Table 1 shows the 2004 United States Department of Energy review of British thermal units (Btu) consumption to provide lighting for the residential and commercial sectors in 1990 and 2002 and the projected amounts for 2010 and 2025.[1] Note that this table does not include expenditures in the transportation and industrial sectors. Also, it is only for lighting of our homes and workplaces, and does not include a number of other illumination costs, including displays, indicator lights on appliances, or associated costs for cooling due to heat generation by our lights. Including all such costs, it has been speculated that lighting leads to about 25% of our yearly energy expenditures. Reference 1 indicates that lighting consumption and its reduction is expected to be the primary focus for the commercial sector until 2025. New technologies such as daylighting and solid-state lighting will lead to more efficient use of energy in the future.

Table 1 Residential and commercial lighting consumption published by United States Department of Energy, January 2004 (NA indicates not available).

	1990	2002	2010	2025
Residential Lighting (quadrillion Btu)	1.0	2.41	2.73	3.07
Commercial Lighting (quadrillion Btu)	NA	3.597	4.103	4.301
Total	>1.0	6.007	6.833	7.371

The efficiency of the design is only a partial answer to the driving factors in illumination engineering. Of nearly the same importance is the distribution of light at the target. Uniformity in position is a common desire (i.e., irradiance or illuminance), but angular uniformity (i.e., intensity) and brightness (i.e., radiance or luminance) often play roles. Nonuniformity is often demanded by governmental bodies, such as the distribution of light for external automotive applications (e.g., headlights and taillights).

Lesser factors that drive illumination system design include color, visual perception, thermal management, fabrication costs, and imaging aspects for visual systems. The inclusion of these factors often run counter to one another, thus making the design of illumination systems complex and demanding. To further complicate the design procedure, optimization and tolerancing are more difficult to implement in comparison to imaging systems. Simply said, the illumination engineer or scientist has an increased importance in the successful design of systems that we use on a daily basis.

The ten papers that make up this *Optical Engineering* special section cover a wide breadth of topics within the field of illumination engineering. The order of the papers starts with design concepts, beginning with illumination systems that have been in use previously and ending with novel design concepts. Next, applications in the field of illumination are presented. The final topic is the imaging aspects of illumination systems.

We start the special section and design concepts subsection with a paper by Rehn on the optical properties of the oft-used elliptical reflector. The performance of the elliptical reflector in conjunction with an extended source is studied, such that the luminance and illuminance distributions can be found analytically at the second focal plane. This procedure removes the cumbersome task of ray tracing while providing guidance for the proper design of elliptical reflectors for the desired application.

The next four papers broach the area of novel design concepts for the design of illumination components. The last two papers use applications to illustrate the design methods presented. The first paper by Benítez et al. discusses the ‘‘simultaneous multiple surface’’ method in three dimensions. This method develops concurrently two free-form optical surfaces for the distribution control of light that is emitted from the optic. Refraction, reflection, and total internal reflection are used to accomplish this goal. This paper is followed by one on the analytic design of lightpipes by Van Derlofske and Hough. They develop a ‘‘finite confinement diagram’’ in order to explain the propagation of light into, through, and out of a rectangular lightpipe, especially those with a bend. With this method first-order design of lightpipe systems can be simplified and made tractable to individuals entering the illumination profession. The paper by Koshel and Walmsley discusses the topic of nonedge ray design. In illumination design, the ‘‘edge ray’’ often drives the design of the illumination system. The choice of this ray set ensures increased efficiency, often at the expense of distribution requirements. An application that suffers from the limitation of the edge ray is the optical pumping of a solid-state gain medium, in which the three-dimensional absorption distribution is of importance. The authors use the goal of efficient optical pumping of cylindrical laser rods to describe and develop this method. The section of novel design concepts ends with a paper by Muñoz et al. that uses the previously presented simultaneous multiple surface design method to develop the prescription for a compact, air-gap collimator for LEDs. The designed optic uses refraction, reflection via a coating, and total internal reflection to accomplish its goal. The authors note that the air gap introduces another degree of freedom in the design process. These optics have a number of applications including consumer and automotive ones.

The next section presents three application papers. The first, by Ries et al., continues with LEDs as the source. In this paper the authors discuss a linear optimization method in order to combine commercially available LEDs of different colors in order to provide the desired composite color. They show how to optimize in addition to the desired color for such parameters as luminous efficacy, color rendering index, and total luminous flux. Next, Lee and Greivenkamp present a method for the measurement of lightpipe systems used for automotive applications, such as in the main console, thermal controls, or stereo. They compare the test result to those from software modeling that includes a well-developed model of the source, lightpipe geometry, and emission surfaces. The third paper in this section by Li et al. discusses the light engine that can be used in systems such as projection displays. They discuss methods to capture the light from the source with a dual paraboloid, to inject the captured light into a homogenizing tapered lightpipe, and to recover the unusable polarization by means of a novel composite polarizer cube arrangement. The goal of the entire system is to efficiently transfer the source light while providing uniform illumination to a potential target, such as a liquid crystal display.

The final section continues the motif of displays, but the two papers in this section treat the imaging aspects of display design, use, and modeling. The first paper by Waldkirch et al. presents the effects of coherence on depth of focus in head-mounted displays. The effects on contrast and image quality are presented. Image quality in the form of text readability is evaluated both with an analytic figure of merit and the results of subjective human experiments. The final paper of this special section by Shaoulov et al. discusses a software model that uses scalar diffraction theory to propagate an optical field in the nonparaxial regime. The illumination source is quasi-monochromatic and spatially incoherent. Simulated results using up to multiprocessor platforms are presented in order to show the performance of the model.

As one can see, the topics presented in this special section are broad, but by no means inclusive. The field of illumination engineering is in its infancy, and I expect future special sections in this area will present many more papers and topics. This special section was borne out of my involvement with the illumination conferences held at SPIE’s Annual Meeting. The number of conferences, contributed papers, and attendance in the area of illumination engineering has been growing steadily at the Annual Meeting. I thank editor Donald O’Shea for the support in the development of this special section. I thank the *Optical Engineering* staff for their tireless work in making this special section a reality. Special thanks goes to the managing editor Karolyn Labes who, over the duration of this special section, taught me a number of nuances of the publication process. Finally, my biggest appreciation goes to the authors and reviewers who ensured the breadth and quality of this special section. Without their efforts this special section would not have been possible.

References

1. Energy Information Administration, *Annual Energy Outlook 2004*, see Fig. 50 (p. 71) for the residential data and Fig. 53 (p. 73) for the commercial data, www.eia.doe.gov/oiaf/aeo/, United States Department of Energy (2004).

R. John Koshel obtained his BS (1988) and PhD (1996) degrees from the Institute of Optics, University of Rochester. Since then, he has held positions in a government lab, academia, and industry. Previously he was director of Optical Engineering Services at Breault Research Organization in Tucson, Arizona. He is currently employed at Spectrum Astro, Inc. in Tucson, where he works on space-based optical systems. His research interests include illumination theory and design, laser design, optimization of optical systems, and ray propagation. He is also an adjunct assistant professor of optics at the Optical Sciences Center, University of Arizona, where he teaches a seminar series on illumination optics. He assists both the OSA and SPIE with leadership functions, including serving on the *Optics & Photonics News* Editorial Advisory Committee and as a chair for SPIE’s ‘‘Nonimaging Optics and Efficient Illumination Design’’ and ‘‘Novel Optical Systems Design and Optimization’’ conferences.